VISUOMOTOR COORDINATION IN SYMMETRIC AND ASYMMETRIC BIMANUAL REACHING TASKS

by

Divya Srinivasan

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Doctoral Committee:

Associate Professor Bernard J. Martin, Chair
Emeritus Professor Don B. Chaffin
Associate Professor Brent Gillespie
Assistant Professor Kathleen Sienko
Research Associate Professor Matthew P. Reed

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ABSTRACT

VISUOMOTOR COORDINATION IN SYMMETRIC AND ASYMMETRIC BIMANUAL REACHING TASKS

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Chair: Bernard Martin

Eye-hand coordination is fundamental to performing any motor activity, from the simplest tasks to skilled operations required of professionals in sports or industry. While coordination of concurrent motor responses has been studied extensively, the factors that drive specific patterns of coupling of the two hand movements are not yet clearly understood. The dissertation discusses the organization of bimanual coordination: patterns of movement initiations, movement durations, and spatio-temporal coupling of hand movements as a function of task demand. A model has been proposed to predict how competing visual demands of both hand systems could be met within constraints of the visual system.

This study investigates the role of visual feedback in mediating control of bimanual movements using two reach tasks, one with each hand, to targets with different accuracy constraints. A strong tendency to temporally synchronize movements of both hands was observed. Although synchronized until peak-velocity, patterns of coordination of terminal phases of movements varied as a function of task difficulty. Spatial symmetry was compromised in favor of temporal symmetry. Patterns of spatial coupling were pre-planned based on the system's expectations about the time of availability of visual feedback for completion of the secondary task. With practice, different eye-hand coordination strategies emerged as a function of task precision. Although both movements were performed simultaneously, feedback resources were prioritized to process movement corrections of only one task at a time. In symmetric task conditions, visual attention was consistently allocated first to the left-hand-task (primary), and performance of the right-hand-task was secondary, dependent on successful performance of the primary task. This behavior indicates asymmetry in feedback requirements of the two hand systems.

An integrated control model of the two hands and gaze system was developed to simulate self-paced bimanual tasks with only high-level inputs. This model sequences movement phases as a function of task parameters and mediates optimal allocation of visual resources to both hands. Combined with an attention-allocation mechanism based on a stochastic probability of successful task completion, the model accurately produces the diverse visuomotor coordination phenomena observed in laboratory (task prioritization, gaze transitions and production of realistic multimode hand velocity profiles).

CHAPTER 1

INTRODUCTION

1.1. Thesis statement

The remarkable faculty of humans to produce coherent actions by simultaneously coordinating both limbs to achieve their individual goals, forms an integral part of our routine behavior. Although each cerebral hemisphere primarily controls the respective contra-lateral limb, the spatio-temporal properties of bimanual movements indicate strong interactions between the left and right limbs. The execution of concurrent motor responses has been studied to characterize these inter-hemispherical interactions. Temporal symmetry (symmetry in time between the two limb movements) has been evidenced in a number of reach, and reach-to-grasp types of tasks, where movements are directed to two separate target objects. Asynchronous coordinative timing has been reported in tasks of relatively higher precision. Previous models of bimanual coordination, such as the functional synergy hypothesis or the integrated competition model, predict either symmetric or asymmetric interactions of the two hands. However, due to varying degrees of overlap of the movements of the two hands, bimanual coordination of movements may involve task-dependent dynamic switching between these two modes of interaction. Since psychology and motor control literature are inconclusive as to the factors that produce symmetric or asymmetric bimanual performance, current models do not account for such an integration of both symmetric and asymmetric interactions of the two hands from the perspective of task performance. Task difficulty, divided attention, lack of visual integration and hand dominance have been pointed out as some potential factors that could affect the degree of synchrony of bimanual movements.

To assess the effects of visual feedback in a bimanual transfer task, an experiment was designed in which object size, target tolerance, and inter-target distance were varied, allowing an examination of how movements are coupled to meet the competing visual demands of the two hand tasks. A control-theoretic model was developed to understand the organization of bimanual coordination, and this model generated hand movement velocity profiles and gaze trajectories in accordance with the observed eye-hand coordination strategies in bimanual reaching tasks requiring visual feedback.

1.2. Applied problem

Rehabilitation of upper-limb function after hemiplegic stroke requires understanding of anticipatory and movement control processes of bimanual coordination. Each year, tens of thousands of survivors of middle cerebral artery strokes in the world emerge with one paretic arm and one healthy arm. They typically receive physical therapy for three months after stroke in the hope of restoring some control to the disabled arm (Reinkensmeyer et al. 1993). Automating portions of their therapy could improve cost, availability, and evaluation. Bimanual rehabilitation, in which a robot assists a disabled hand in cooperating with a healthy hand, would enable patients to use the robot as a specialized machine for therapy (Lewis et al. 2009). Insight gained from the device may also apply to the design of orthoses. However, designing rehabilitative devices that interact with the one healthy arm would require an understanding of how one arm would coordinate with the other in terms of the spatio-temporal aspects of movement kinematics, and also how each independent movement control would be affected by constraints that arise from sharing resources such as vision and torso, common to both the manual systems.

Another major motivation for studying bimanual object manipulation tasks is improving digital human simulations for ergonomic applications. Most industrial tasks involve workers or operators using both their hands to interact with parts or tools in their environment. They perform separate, but coordinated tasks with each hand, such as placing a fastener in a hole and then applying a tool to the fastener. In an attempt to improve the current ability of digital human modeling software to simulate posture and motion for ergonomic analysis, considerable efforts have been made in the HUMOSIM laboratory on the development of a general framework that can simulate complex tasks involving multiple movements and object manipulations with only high-level inputs (Reed et al. 2006). A model to automatically simulate the sequencing of movement components in bimanual tasks and generate velocity profiles with only high-level task commands would thus be an important and significant contribution to current digital human modeling tools in this context.

1.3. Theoretical problem

Our evolutionary history indicates that long before our ancestors possessed the capacity for language or abstract learning, they could "move", purposefully, and in relation to objects and places in the environment. Motor learning, i.e., how the central nervous system evolved to learn to move and the basic neuronal and synaptic mechanisms that evolved in this process, is believed to provide the basis for all other forms of learning and knowledge. Fundamental aspects of our behavior, such as the ability to use tools, originate from neural specialization for perceiving, reaching, grasping, recognizing and categorizing objects. The theoretical and computational integration of the principles of biology, physics, mathematics and engineering to understand how the CNS generates such movements is a fascinating problem. The function of each mechanism under study is directly accessible, since the observation of an action reveals its goal and thus gives us access to its biological significance.

The earliest researchers in this field of motor control and neuroscience have observed that even the simplest movements produced by an animal, such as the reflex response elicited by cutaneous stimulation in a frog, appear to be 'intelligent' actions because of their purposeful organization.

For many actions that are brief in duration and produced in stable, predictable environments, humans are known to usually plan movements in advance, and then execute the actions with a set of pre-structured motor commands often referred to as a motor program (R. Schimdt, 2000). There is very little conscious control of such movements once they are initiated. The action just seems to run its own course without much modification. This type of control that involves the use of a centrally determined, pre-structured set of commands dispatched to the effector system and run without feedback to control rapid, discrete movements is known as open-loop control. The reason we need such open loop movements to overcome the sensory-motor delays involved in making movements that require feedback based corrections. The type of control that involves the use of sensory feedback and depends on error detection and correction processes to maintain the desired goal, used to control slow, goal specific movements is known as closed-loop control.

Most actions in our life, especially reaching and grasping, depend on a balance of initial programming and subsequent correction. Initial programming is partly based on visual perception of the objects that need to be grasped. The visual information is used to decide whether to pick up objects with one or two hands, how to orient the hand and bring it around the objects to be grasped, etc.

Even simple reaching movements may include multiple task components, other than moving the hand toward the goal target. For example, reaching involves the movement of the head and the eyes to capture images of the environment and build an internal representation of the space in which hand movements are planned and guided. It has been shown that head and/or eye movements are modulated by the movement of the whole body and the hand (Delleman, Huysmans, and Kujit-Evers, 2001; Tipper, Howard, and Paul, 2001; Chapter 5). Furthermore, studies indicate that the whole body and/or hand movements are also adjusted to accommodate visual perception of the environment (Peterka, & Benolken, 1995; Cohn, DiZio, & Lackner, 2001; van der Kooij, Jacobs, Koopman, & van der Helm, 2001).

Thus, the central nervous system, while planning and executing a movement, simultaneously controls multiple subsystems that pursue individual and shared goals (guiding the hand, displacing the gaze, etc) in order to achieve the general aim of the task (reaching for the target). ‘Coordination’ can be understood as the organization of the cooperation among multiple subsystems involved in movement control, with different individual goals achieved such that certain common system constraints are met.

1.3.1 Reaching

Much of the research on control of hand movements has been concerned with the simple task of moving the hand from one position to another, generally as quickly and accurately as possible. This task was first studied in detail in the late nineteenth century by Woodworth (1899). He hypothesized that an aiming movement is composed of an initial ballistic phase (achieved through an impulse control), followed by a feedback-based homing-in phase (achieved by ‘current’ control) as illustrated in fig 1.1.

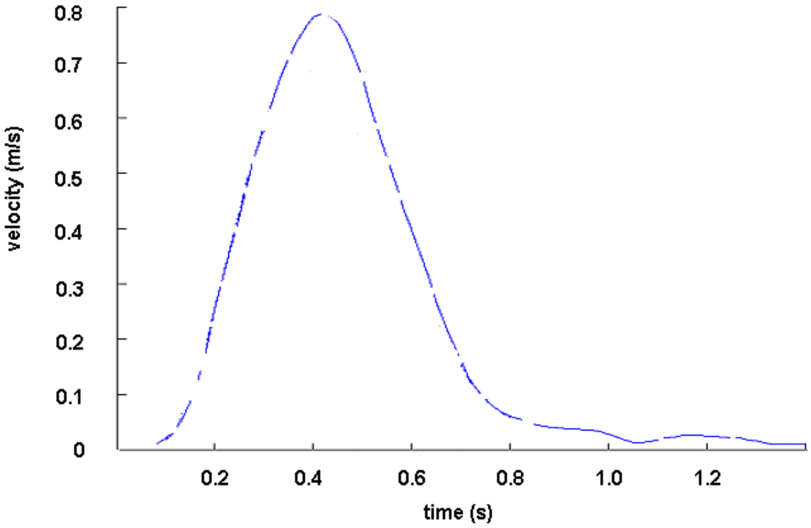


Fig. 1.1: Typical velocity vs. time profile, composed of initial ballistic phase and later corrections

This idea was pursued by a number of researchers until Paul Fitts (1954) developed one of the most fundamental principles of movement behavior, the speed-accuracy trade-off, by linking the time required to complete a pointing movement to the difficulty of the task, as defined by the amplitude and precision constraints imposed. This relation can be summarized in the following equation:

$$MT = a + b \log (2A/W) \qquad (1.1)$$

where MT denotes the movement time, A denotes the amplitude or distance of movement, W denotes the width of the target, and a and b are empirical constants. The term log(2A/W) is called the index of difficulty (ID) and equation (1) implies that MT increases linearly with ID.

Although originally derived from a series of alternating stylus-movements between two targets, Fitts' law has been found to been used to satisfactorily predict movement times for many other tasks as well: discrete ('one-shot') aiming movements (Fitts and Peterson, 1964), transferring pegs over a distance to be inserted into a hole (Annet, Golby & Kay, 1958), throwing darts at a target (B. A. Kerr & Langolf, 1977), carrying out aiming movements under water (R. Kerr, 1973), and even manipulating objects under a microscope (Langolf, Chaffin & Foulke, 1976).

While the simplicity of the relation linking MT and ID is appealing and robust to context changes, several definitions of ID and interpretations of speed-accuracy tradeoff have been proposed over the years (reviewed in Meyer et al., 1990, Plamondon & Alimi, 1997). While the original Fitts formulation is most popular in experimental psychology, the Shannon formulation:

$$MT = a + b \log(2A/W + 1) \qquad (1.2)$$

which accounts for both the signal and the noise is most preferred in human-computer interaction (MacKenzie, 1989) and kinesiology.

Further, it has been shown that for very small movements or movements to large targets, Fitts' law is violated (Klapp, 1975). It has also been observed that Fitts' law is limited to tasks in which $2 \leq ID \leq 7$. The violation is explained by the fact that the closed-loop phase of the movement is not present in such movements that require little spatial accuracy or very short duration. Schmidt et al. (1978 and 1979) examined speed-accuracy tradeoffs and Fitts' law in rapid reaching tasks. They also observed the limiting case where Fitts' law is violated and the relationship is not linear for movements controlled entirely by an open-loop mode of control.

Although many motor control models have been developed to explain Fitts' law, they could only explain the law partially and do not satisfactorily account for all the data on manual aiming. The optimized initial impulse model, introduced by Meyer et al. (1988) was a hybrid of the iterative corrections model (Crossman & Goodeve, 1963, 1983; Keele, 1968) and the impulse variability model (Schmidt, Zelaznik,1979) and was the most successful in explaining the observed effects.

This model explains Fitts' law from an optimization perspective – where-in subjects attempt to optimize both speed and accuracy. They showed that Fitts law is actually a special case of a more general relation:

$$T = a + bn\,(D/W)^{1/n} \qquad (1.3)$$

where T is the total movement time, D is the distance from a starting point to the center of a target, W is the width of the target, n is the number of sub-movements, and a and b are constants. Fitts' law is derived when n approaches infinity. Although subjects do not make an infinite number of sub-movements, Fitts' law represents a limiting condition and provides a reasonably precise way of fitting movement-time data.

This seems to indicate that even when people engage in mundane tasks, they employ sophisticated strategies to optimize performance and even simple tasks may not be computationally trivial. Hence, although Fitts law is an extremely useful tool in assessing the overall movement performance, subsequently, several attempts have been made to understand the underlying processes governing behavioral organization. In the domain of perceptuo-motor control, it is widely accepted that a more fine-grained window into these processes is available through study of the kinematics of movements, rather than an exclusive focus on movement time (MT).

1.3.2. Temporally unconstrained movements

Most natural human movements, typical of routine behavior are usually ‘unconstrained’. They seldom follow the optimal constraints of minimum speed and maximum accuracy. In most ergonomic studies associated with industrial human movements or routine behavior with no emphasis on speed, humans are not motivated to optimize the speed-accuracy curve as described by Fitts’ law.

In a study requiring only spatial accuracy of 2D movements to targets located on a horizontal plane, it was observed that feedback corrections can occur in any phase of the movement, and the timing of these corrections varies with target location and individual strategy (Srinivasan et al., 2006). Joint movement initiations (coordination) are not necessarily synchronized, contrary to previous reports (Hoff & Arbib, 1993; Vercher et al., 1994; Sailer et al., 2005).

A kinematic model of coordinated movements of the head and upper extremities was developed for three-dimensional unconstrained seated reach tasks (Kim 2005). This model hypothesized that unconstrained three-dimensional movements are multi-phasic, and can be modeled by the coordination of multiple subsystems with specific goals. Three distinct phases were identified using reach movement kinematics:

1) Lift-off phase: Fast head movement followed by, or concomitant to, a preparatory hand displacement
2) Transport phase: Compensatory head movement to maintain aiming direction, accompanied by hand displacement to near the target
3) Landing phase: Slow approach to the target, mostly along the line of sight

Movements within each phase are controlled by phase-specific modes, including feed-forward direction-based, feed-forward posture-based, and feedback inverse kinematics modes, respectively. The presence and duration of each phase may be context dependent.

Thus, going beyond empirical speed-accuracy tradeoff relationships and using kinematics to understand movement organization is valuable in modeling unconstrained movements.

1.3.3. Grasping

Prehension is a highly developed motor skill that affords the study of how components of a movement are coordinated to produce the near endless variety of acts that serve to acquire objects in near body space. The prehension task has been viewed as being composed of two main phases:

(i) Transport phase: The phase in which the hand is brought to the appropriate location in the vicinity of the object

(ii) Grasp phase: The phase in which the fingers form a grip, in anticipation of the object to be grasped

The added complexity of coordinating a prehension task as compared to a reaching task has led to the development of certain interesting theoretical perspectives on movement control and coordination. Two main classes of theoretical frameworks have been developed to explain how the transport and grasp phases are coordinated during prehension movements:

(i) Those suggesting that the coordination of movement components is planned in advance of movement onset and based upon temporal synchronization

(ii) Those proposing that coordination is achieved by the on-line control of movement parameters based upon continuous sampling of spatial information

While both these frameworks can be extended and applied to any kind of movement in general, and are not restricted to just reach and grasp movements, they have originally been proposed using the context of grasp movement coordination.

1.3.4. Pre-planned coordination strategy

One of the most influential of this framework is Jeannerod's `visuomotor channels hypothesis' (Jeannerod, 1981, 1984). In this view, prehension consists of two independently computed components: a transport component in which the limb is transferred to the region of the target object, and a grasp component in which the hand is preshaped and oriented so as to facilitate gripping the target (Jeannerod, 1984). These components are assumed to be based upon separate visuomotor channels which provide different sources of information about the perceptual properties of objects. A key aspect of Jeannerod's original proposal was that the independently computed transport and grasp phases were coordinated by a common kinematic plan, which is generated centrally, and in which the temporal unfolding of the grasp phase is linked to the time frame computed for the transport phase. An important prediction of this model, however, was that experimental manipulations that affect the computation of the grasp, e.g. changes to object size, should not have consequences for transport kinematics.

Hoff & Arbib (1993) suggest that separate estimates of the time needed to complete the transport and grasp are relayed to a higher order control system responsible for coordinating lower level movement elements (schemas). It is posited that perceptual schemas exist that when activated define the location, size and orientation of the to-be-grasped object. The outputs of these schemas are used by two motor schemas, one to control the transport component and the other to control the grasp component. A coordinated control program is responsible for controlling the time-varying interaction of this act, and serves to temporally link the transport and grasp components (fig 1.2). One characteristic Arbib feels is important for his coordinated control program for prehension is the fact that most movements have two phases - ballistic and feedback based. He posits that the ballistic phase is a product of a feed forward system that can define the initial state of the limb and the goal and then determine a movement that will approximately achieve the goal. Feedback processes then must be used during the second phase of movement to accurately complete the grasp. Both the transport and grasp components are seen as having these two phases of control. Two points should be noted about both the Jeannerod and the Hoff & Arbib models: the clear emphasis on movement planning processes rather than on-line (continuous) control and the proposal that movement duration is the coordinating factor.

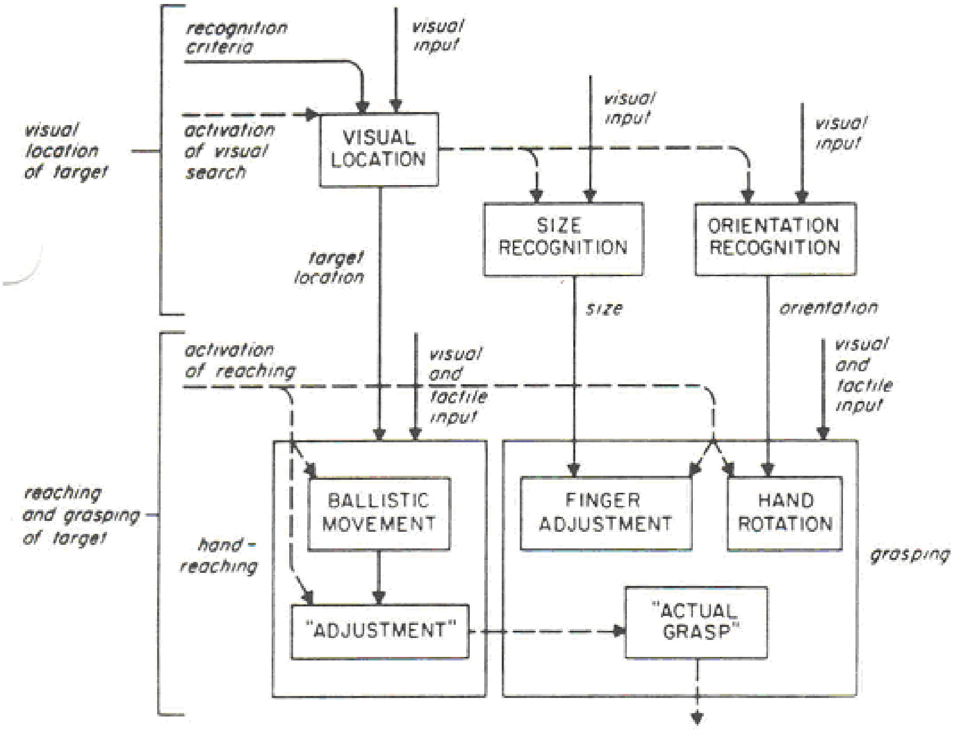


Fig. 1.2: The Arbib model accounting for independence of segmental components. Parallel processors deal with the various aspects of the object to be grasped (spatial location, size, orientation). These processors are connected with controllers for the corresponding segmental movements (ballistic movement, finger adjustment, hand rotation) – From Arbib, 1981

Martenuik (1987, 1990) considered prehension as a multimovement act composed of several components, which through learning, have become integrated into a system that can accomplish the same task in many different ways. Prehension, like other skilled movements, is an over complete system and as such can consistently attain a movement goal through variable movements of the involved components - so-called motor equivalence. Thus, relations among components in a multimovement system are functional rather than fixed. This means that the relations among the components may differ depending on such variables as the experience (knowledge base) of the performer and the specific prehension task including object properties and instructions from experimenters. This model allows feed forward control, where the deleterious effects of errors or perturbations can be counteracted before the movement outcome is influenced

(Abbs et al. 1984; Houk and Rymer 1981). But this model again suggests a coordinating structure and suffers from the same problem as the Arbib model.

1.3.5 Information-based model of natural prehension

An alternative to the temporal planning models are those proposing that coordination is based upon changing spatial position. A noteworthy feature of these models is an emphasis on the on-line or continuous control of movement variables (e.g. velocity, grip aperture etc.), and the proposal that the later stages of reach-to grasp movements may operate within object-centered rather than body-centered coordinates. One such model proposed by Bootsma and colleagues (Bootsma & van Wieringen, 1992 ; Zaal, Bootsma & van Wieringen, 1998) proposes that control of transport and grasp is dependent, in each case, upon a common source of perceptually derived information the rate of change in the distance between the hand and target object (often alternatively referred to as the remaining time to contact). Coordination is therefore not planned, but instead arises as a consequence of each component sharing a common information signal.

After having started out on the basis of direction and distance to target information only, the self-generated information concerning time-to-contact between hand and object dictates that the hand be opened and closed within the specified interval. So the size of the object would influence only the latter part of the transport phase. The important difference between this hypothesis and the previous models is that there is no pre-structured kinematic plan and the movement time is generated by the movement itself. Hence coordination just emerges automatically as both the transport and grasp phases are ultimately geared to the same source of information: time to contact between hand and object (based on the current velocity and distance of the hand relative to the grasp object).

1.3.6. Visual Guidance

Rapid aimed limb movements depend critically on information obtained from the eyes. Beginning with the classic research by Woodworth, numerous investigators have studied various aspects of visual-feedback processing related to the production of aimed limb movements.

Gaze fixation strategies are useful because they place the visual target on the part of the retina (the fovea) with the most densely packed sensory apparatus, while temporarily removing the added burden of spatial updating for gaze shifts. Moreover, fixating gaze at particularly task-relevant points in a coordinated sequence allows for periods in which the brain can calculate the geometric relationships between the external world (through vision) and the internal world through proprioception (Johansson et al., 2001). The temporal coupling of eye and hand movements varies in a task-dependent manner, presumably to optimize the useful flow of visual information for a particular task (Fisk and Goodale 1985; Land and Hayhoe 2001; Rossetti et al. 1993; Sailer et al. 2000).

Land et al. (1999) examined gaze-hand coordination in natural object manipulation tasks and found that subjects directed gaze almost exclusively towards objects involved in the task. They considered four functions of gaze fixation in manipulation tasks: locating objects, directing the hand or object in hand to contact an object, guiding contact between two objects that are approaching each other, and checking the state of task-related variables. An analysis of the coordination between gaze behavior, fingertip movements, and movements of the manipulated object in a study by Johansson et al. (2001) suggested that gaze supports hand movement planning by marking key positions to which the fingertips or grasped object are subsequently directed. The salience of gaze targets is believed to arise from the functional sensorimotor requirements of the task. They also emphasized that gaze control contributes to the development and maintenance of predictive motor control in manipulation.

1.3.7. Bimanual object manipulations

Many skilled manual activities in humans involve the use of both hands. However, although the topic of inter-limb coordination has been of interest for nearly a century, most studies of upper limb movements have examined unimanual rather than bimanual actions.

Bimanual coordination has most often been approached in the context of symmetric or asymmetric interactions of the two hands. Guiard (1987) defined an asymmetric bimanual action as one in which the two hands are involved in qualitatively different manual contributions. He introduced the concept of lateral preference, to denote preference for one of the two possible ways of assigning two roles to the two hands, as an alternative to the concept of manual superiority, and thus proposed that all unimanual tasks are just limiting cases of bimanual tasks. Guiard outlined the following two principles to determine the relationship between subtasks assigned to the two hands, i.e. division of labor:

(i) The non-preferred hand (often the left hand) plays a postural role in keeping an object steady while the preferred hand (right) executes manipulative action on it. Thus the motion of right hand typically finds spatial reference in the results of the left hand's motion.

(ii) The left hand's contribution to current action starts earlier than that of the right hand (since it represents the spatial reference for the right hand)

Hinckley (Hinckley et al. 1997) reported similar observations and concluded that in general, 'cooperative' bimanual action is asymmetric in nature. However, the analysis of cooperative bimanual actions is out of the scope of the current study, which focuses on bimanual tasks in which the two hands have qualitatively similar roles to perform, such as bimanual reach or reach-to-grasp movements.

1.3.8. Bimanual reach-to-grasp studies

Most studies of bimanual movements have been restricted to 'single phase' aiming movements, tasks where both hands are used to acquire a single object or simple reach-to-grasp movements in which both hands are used to acquire a pair of objects.

When study participants were not explicitly instructed to synchronize their hands during bimanual aiming tasks, they tend nevertheless to do so (Keele, 1986). Consequently, movement duration as well as time of movement initiation are similar for both hands. Due to this tendency to synchronize the hands, when tasks of mixed difficulty are performed, Fitts' law is violated. It has been observed that the hand reaching for the difficult target takes less time than it would do if the other hand were also reaching to a difficult target, whereas the hand reaching to the easy target takes more time than it would, if the other hand were also reaching to an easy target. On the basis of evidence such as this, Kelso et al. have proposed that during bimanual movements, the two limbs are coupled together with a single coordinating structure, an organized functional group of muscles, and are thus constrained to act simultaneously.

However, Marteniuk et al. (1984) re-evaluated the same data and used their own results to suggest that hands are significantly less synchronized than previously reported. They propose that the hands are not coupled to a single timing structure, but are controlled separately; the similarity between the movements of two hands under mixed-difficulty conditions arises as a result of neural cross-talk between the hands.

The literature is equivocal as to whether reach-to-grasp movements involve more limb-specific control and greater asynchrony than simple aiming movements (Castiello, Bennett & Stelmach, 1993). Jeannerod (1984) found that movement onset and duration were closely synchronized when reaching to grasp. In addition, the timing of maximum hand velocity and maximum grip aperture were also similar for each hand.

A more recent study by Jackson et al. (1999) found that during the execution of concurrent motor responses, kinematic measures are unaffected by whether the actions required of each hand are congruent or incongruent, although there is an overall cost associated with carrying out two movements simultaneously. Thus, in reach-to-grasp movements, movement durations and onset times were synchronized irrespective of whether targets required the same or different levels of difficulty, thus supporting Kelso's findings. Mason's recent investigation (2007) on multiphasic bimanual movements in reach-to-grasp place tasks and reach-to-grasp toss tasks to determine the effect of task context and assimilation effects on coordination also found movements of the two hands to be synchronized.

From a modeling perspective, both the temporal planning models in which coordination of movement components is pre-planned and the continuous control models of online control of movement parameters based on the continuous sampling of spatial information could not be satisfactorily applied to bimanual prehension movements. This could be due to the processing demands required in the continuous control case during bimanual movements.

1.3.9. Integrated Competition Hypothesis

Duncan, Humphrey & Ward (1997) proposed the integrated competition hypothesis which states that visual information processing related to the two different objects compete with one another and that this competition is characterized as interference in which the efficient processing of each object is impaired. According to this theory, one obvious limiting factor during bimanual prehension movements directed towards different objects would be the visuomotor demands involved in attempting to continuously sample two independent ‘remaining time-to-contact’ hand-target separation signals of each hand. One way in which the sensorimotor system could achieve this is by adopting an intermittent sampling strategy during bimanual movements, in which the remaining time-to-contact signals is independently sampled for each hand by intermittently switching attention between target objects. But this indicates that there should be no additional cost of performing incongruent compared to congruent movements. This model also predicts sequential reaches, which is clearly violated in many cases.

1.3.10 Functional synergy hypothesis

An alternative solution, which avoids the problem of having to concurrently monitor two remaining time-to-contact signals, is for the sensorimotor system to reconfigure the task description so that only one time-to-contact signal needs to be monitored. Kelso’s model suggests that this could be achieved by coupling the two limbs together so that they are constrained to act as a single functional unit. This would mean that each limb would commence moving at the same time, but move at different velocities, so as to arrive at their respective targets simultaneously. Thus, according to this model, the two hands could never arrive at their respective targets at different times.

An advantage of this model would be that only one object needs to be viewed to derive a remaining time-to-contact signal. However, within this model, time to contact could be no longer based on visual cues signaling the position of each hand relative to the target, but might instead be based upon a motor error signal between a visual target and the felt position of the limb, thus suggesting a very important role for proprioception in coordinating bimanual movements.

This model is also consistent with the movement planning models proposed by Jeannerod (1981, 1984) and Hoff & Arbib (1993). Since the movements would have to unfold within a common movement duration, the processes involved in generating the complex movement plan are assumed to be completed prior to movement onset. This implies that there should be minimal differences between unimanual and bimanual movements. However, Jackson et al. (1999) observed a consistent advantage for unimanual over bimanual movements in contradiction of Kelso’s hypothesis.

While the temporal symmetry predicted by Kelso’s model has been observed extensively, this temporal symmetry has been observed to break down in high precision tasks, thus indicating that the assumption of functional synergy between the two limbs may be unrealistic. However, on the other hand, continuous intermittent sampling of the two targets predicts necessarily asymmetric times of movement – a result that has been refuted by multiple observations of symmetry. Hence, although bimanual tasks have been studied extensively, there is no model as yet that explains the observed movement kinematics.

1.3.11 Simultaneous motions as treated in Methods-Time-Measurement systems

While the models and methods described in the previous sections were from a motor control perspective, simultaneous motions have also been studied in industrial work analysis settings.

Methods-Time Measurement (MTM) is a predetermined motion time system that is used primarily in industrial settings to analyze the methods used to perform any manual operation or task and, as a byproduct of that analysis, set the standard time in which a worker should complete that task. In the MTM system, the bimanual nature of operator motion patterns is recognized in the following manner. The table ‘simultaneous motions’ that is included as part of the MTM data is used to indicate to the practitioner whether or not he should expect simultaneous performance of any given combination in the following way:

1. If the table indicates that the two motions may be performed simultaneously under the given conditions of practice, this suggests concurrent performance of the two motions, which implies that the time allowed for the motion combination is the longer of the two times.

2. If the table indicates that the two motions cannot be performed simultaneously under the given practice conditions, this suggests successive performance of the two motions, which implies that the time allowed for the motion combination is the sum of the times for the two motions.

Thus in the MTM system, if two motions cannot be performed simultaneously, they are assumed to be performed successively. Deeming this treatment of synthesizing bimanual activity to be unrealistic, and its implicit assumptions to be unjustified, an exploratory study performed by Edward Krick from Cornell University considered an important question: how much should the left and right hand motions overlap to justify considering them ‘simultaneous’? In order to determine the effects of bimanual-ness to synthesize work performance times, the investigators hypothesized that the following variables will have a significant effect on the performance of bimanual activities. The effect of each of these variables on performance time is dependent upon the independent variables of the task, such as the control required, symmetry of motions and the practice involved.

1. **Overlap:** The extent to which two given motions may be overlapped will have an effect on the time it will require to perform that pair of motions. The degree of overlap that may be expected depends upon:

(i) The visual requirements of the elements, i.e., if, when and how long vision is required for each of the motions. If the eyes are required to direct only one motion, then complete overlap may be expected. If vision is required by both motions, but at different times, then again complete overlap may be expected. If however, vision is required by both motions and at the same time, i.e., there are conflicting needs for vision, then the motions can only be partially overlapped.

(ii) The visual angle between the two points at which visual guidance is required simultaneously. This factor affects the degree of overlap in a complex manner. Certain motions can be wholly or partially completed with only peripheral visual guidance. It is then possible to direct one motion with the eyes focused upon the terminal point of that motion while another motion is completed simultaneously with the aid of peripheral vision. Thus, whether and to what extent visual angle aids overlap depends on how effectively one motion can be performed with peripheral vision.

(iii) Amount of practice is an important variable affecting the degree of overlap that may be attained. Additional practice makes it possible to fulfill the visual requirements of a motion earlier /later relative to the motion itself, and in lesser time. This sometimes permits the eye to move to the next motion’s terminal point even before the first motion is completed, thus increasing the overlap between the two ‘vision requiring’ motions.

2. **Interaction:** Interaction is a change in motion performance time arising solely from the fact that the body is executing two or more movements concurrently. It is expected to vary with the following factors:

(i) The control involved in the motions: The MTM association research report indicates that the time for a given motion increases as the amount of control in a movement of the other hand is increased.

(ii) The symmetry of the motions: Interaction is expected to increase with increased dissimilarity of the two motions with respect to type of motion, direction, distance, control, body limb etc. This is due to the body’s natural preference for symmetrical movements.

(iii) The number of motions being performed simultaneously

(iv) The degree to which motions are overlapped

(v) The amount of practice involved

3. **Balancing tendency:** The tendency of beginning and ending points of motions to be accelerated or retarded in an attempt to bring movements of the two hands into synchronism. Thus this tendency delays the termination of some motions, and sometimes accelerates others, in an attempt to synchronize the two motions. So if the terminal points of the two motions are reasonably close, the motions will probably be adjusted to terminate simultaneously. In this context, the degree of motion overlap and practice appear to have a considerable effect on the

balancing tendency. As practice increases, it was observed that the operator finds it easier to perform motions out of synchronism, and can resist the balancing tendency better.

Thus, in conclusion, according to this exploratory study, the major determinants of the performance time for a pair of simultaneous motions are the individual motion times themselves and the extent to which these motions may be overlapped. In turn, the major determinants of the extent to which the motions may be overlapped are thought to be the visual requirements of those motions under the particular conditions of practice, and the visual angle between the two terminal points. Because of the importance of vision in the determination of the bimanual motion pattern, it was concluded that this variable would be the most deserving of study in any subsequent investigation into bimanual motion patterns.

1.4. Research Objectives

The objective of my research is to understand the organization of visuomotor coordination in tasks involving bimanual object manipulations. Routine bimanual tasks require the coordination of multiple components across multiple concurrent actions. In an attempt to account for the dynamic switching between multiple modes of interactions of the two hand movements, the specific factors that would drive symmetric or asymmetric performance in qualitatively symmetric bimanual object manipulations are first investigated. The effect of task conditions on hand kinematics and coordination patterns is then modeled using a control theoretic approach, in which the control of bimanual movements is modeled from a resource-limitation perspective. Feedback of the sensory consequences of movements is assumed to be obtained mainly from visual and proprioceptive sources. While proprioceptive information could be obtained independently for each hand movement, foveal vision is modeled as the bottleneck that causes the switching from symmetric to asymmetric coupling of the two hand movements.

1.4.1 Model hypotheses

The central hypothesis of this model of bimanual coordination is that upper extremity coordination in bimanual tasks is primarily mediated by the availability of visual resources. The coordination of visual and left & right manual subsystems, each with its specific goals, produce *multiphase movements* in bimanual tasks. An understanding of the sequencing of movement phases as a function of task parameters and the allocation of resources common to the different subsystems would enable the development of a model that could predict the scheduling of movement components and simulate self-paced bimanual tasks with only high-level inputs. The following set of hypotheses has been developed from an understanding of the material presented in the background section and some pilot data collected at the HUMOSIM laboratory:

- The major determinants of the performance time of a bimanual task are the individual movement times of the two hands and the extent to which these motions may be overlapped
- In turn, the major determinants of the extent to which the two movements may be overlapped may be:
  - The visual requirements of the two movements under the particular conditions of practice
  - The distance of separation between the terminal points of the two tasks which determines the quality of peripheral vision available for one task when the other is being executed and hence, how well visual demands of the two tasks can be integrated
- There is a tendency to maximize the synchronization of the movements of the two hands, within the limits of task and resource constraints
- This synchrony is maintained until a resource limit is reached, that is, until one hand needs the visual resource currently being used by the other
- An increase in task precision demand exercises a constraint on the available resources by increasing visual demand and hence breaks down the synchrony between the two hand movements, resulting in sequential movement termination.

Fig 1.3 shows a basic control scheme for a bimanual movement in which coordination between the two movements is mediated by a limited-resource model of visual feedback.

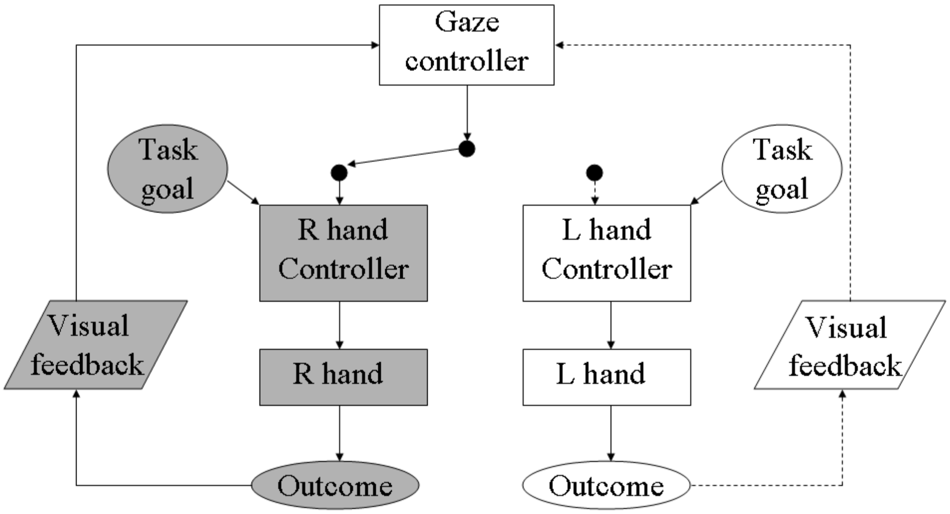


Fig. 1.3: Bimanual control model based on sharing of visual resources

1.4.2. Specific Aims

SA1. Conduct an experiment to investigate factors that may drive symmetric performance or force asymmetric interactions of the two hands as a function of task precision.

Although transition from a symmetric to an asymmetric mode of coupling between the two hand movements has been negated, when and why this happens is largely unanswered. The time at which the mode of coupling changes (during the course of the movements), and the mechanisms that could lead to this switch, and how these change with change in the task's precision demand are investigated experimentally. The task precision demand is characterized in terms of the object size, target tolerance and distance between targets, in a bimanual task in which subjects are required to transfer two objects, one with each hand, from their starting locations to respective target locations of different sizes. The precision demand of the tasks is varied in order to manipulate the visual feedback requirements of the tasks of each hand. The visual feedback requirement of each task is graded from a very low level at which available sources of feedback information can be shared and symmetric performance is expected, to extremely high levels that would divide the subjects' attention, in order for us to be able to investigate how effectively visual information can be integrated and how this in turn influences the kinematics of hand movements. A set of right handed and left handed unimanual trials will be used to analyze the cost of a bimanual movement and how concurrent performance affects the task kinematics of each hand.

SA2. Develop a model to predict hand velocity profiles and gaze transitions in bimanual tasks with visual feedback.

This control model would simulate routine one or two-handed object transfers in terms of task parameters by coordinating the scheduling of resources, predicting the sequencing of movement phases, nature of their interactions (serial/parallel), and initiation and duration times of the two hand movements, with respect to one another. With the combination of the kinematic and eye-movement data from the experiments, and the behaviors produced by the model, an attempt would also be made to understand more general principles of coordination, such as:

(i) Whether the observed patterns of coordination are pre-planned with control being anticipatory, or whether coordination emerges during the course of the movement, with online control, and

(ii) Whether a higher level coordination controller is needed to sequence the two hand movement phases with respect to one another, or whether the control of the two manual systems could be automatically generated by using principles such as queuing of feedback information without the need for an explicit coordination controller.

1.5 Pilot Study

A pilot study was designed to investigate a general bimanual 'reach-grasp-place' paradigm, in which subjects performed dual-handed object manipulations with varying visual demands and performance constraints. Visual demands of the sub-tasks, and their associated precision requirements were expected to have a strong effect on the way bimanual activities are sequenced, in tasks involving such complex visual and manual demands.

The objective of this study was two-fold:

(i) To confirm the importance of visual feedback to mediating bimanual coordination and identify factors that could specifically drive symmetry / asymmetry of the two hand movements, and

(ii) To understand the general range of tasks and precision levels at which the need for visual feedback forces transition from one mode of coupling to the other

1.5.1 Procedure

Two right-handed subjects, a 25-year-old male and a 29-year-old female, participated in this experiment. Three tables were placed around the subject: One to the right, one to the left and the third in front, perpendicular to the sagittal plane. An eight-camera Qualisys® motion capture system was used to record kinematic data sampled at 60 Hz. Reflective markers were placed on selected body landmarks to record the subject's hands, arms, torso and head movements. Eye movements were recorded simultaneously using a head mounted eye tracking system (ASL Eye Trac 6.0). The direction and point of gaze were also monitored on a video screen.

Subjects were seated and asked to perform object manipulations that involved moving the hands from an initial position (on their laps) to grasp a pair of cylindrical objects using a pinch type grip, and transferring them from their starting locations to their respective target locations, and then returning their hands to the initial positions. The left hand always picked the object on the left and moved it to the left target location, and vice versa for the right, i.e., the task did not require any crossing over of the two hands. Although they were not explicitly instructed to manipulate the objects simultaneously, the tasks were symmetric in principle, and a symmetric performance was expected. Several placement precision demands were required to affect the visual demand and divide visual attention. This procedure helped investigate how effectively visual information is integrated. Movement speed was not specifically constrained: subjects could move at a self-determined pace. The only constraint was on accuracy, with zero error tolerance.

Two pairs of lightweight cylinders, of diameters 30 mm (Ob 1) and 60 mm (Ob 2), and 120 mm height, were used as objects to be manipulated. Target locations consisted of circles drawn on the surface of the table. The diameter of these target circles and their locations were varied. The initial positions of these cylinders were predetermined locations on one or more of the three tables, while all the targets were always located on the center table. For each pair of objects: The pickup locations of the objects for the manipulation task were one of the following four conditions:

1. 50 mm apart, RR (both on the right table)
2. 50 mm apart, LL (both on the left table)
3. RL (one on the right table, one on the left table)
4. 50 mm apart, CC (both on the center table)

The final target locations constituted the following four conditions:

I. Target circle diameter = object diameter (30mm if Ob1, 60mm if Ob2)
    a. Distance between target locations=30 mm (C1)
    b. Distance between target locations=200mm (C2)
II. Target circle diameter = 2Xobject diameter (60mm if Ob1,120mm if Ob2)
    a. Distance between target locations=30 mm (C3)
    b. Distance between target locations=200mm (C4)

Thus for each pair of objects, a total of 16 test conditions: (RR, LL, RL, CC)X(C1, C2, C3, C4) were tested for each subject. The experimental setup is illustrated in fig 1.4.

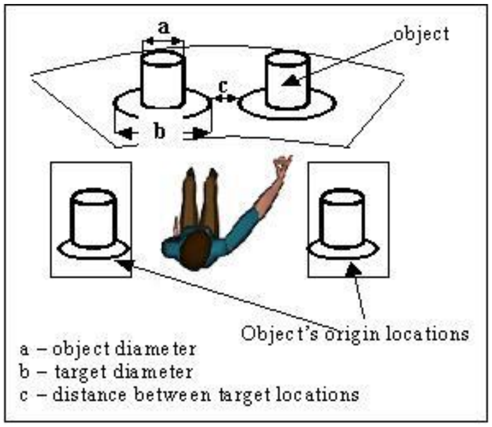


Fig. 1.4: Experimental Setup

All trials were randomized and each trial was repeated eight times. Inter-trial intervals were of approximately 15 seconds. Before each trial, the subject was allowed to see the locations of the objects and the targets. The last three repetitions of each condition, by which the behavior had reached a steady state, were used for analysis.

1.5.2. Data Analysis

The kinematic data from the markers placed on the wrists of the right and left hands were used to calculate the onset and end times of movement phases. The movements were found to be multi-phasic: the typical velocity curves in fig 1.5 illustrate the major phases and sub-phases of each movement:

1. Object pickup phase
    i. Reach phase
    ii. Grasp phase
2. Object transfer phase
    i. Transport phase
    ii. Place phase
3. Hand-Return phase (return to initial location)

The following definitions were used to determine the onset and end times of each phase:

- O1 (Onset of object pickup phase) corresponded to the first instant in the wrist velocity profile when the resultant magnitude of the velocity exceeded 5 mm/sec.

- E1 (End of object pickup phase) corresponded to the instant between the grasp and transport phases where the minimum magnitude of resultant velocity occurred.

- O2 (Onset of object transfer phase) was defined as the instant after E1 (i.e. point of minimum velocity) after which the velocity consistently increased in magnitude. In other words, it was the point of reversal of velocity magnitude. O2 and E1 were found to coincide in all cases.

- E2 (End of object transfer phase) was the first instant at the end of the object transfer phase where the hand velocity was lesser than 5mm/sec.

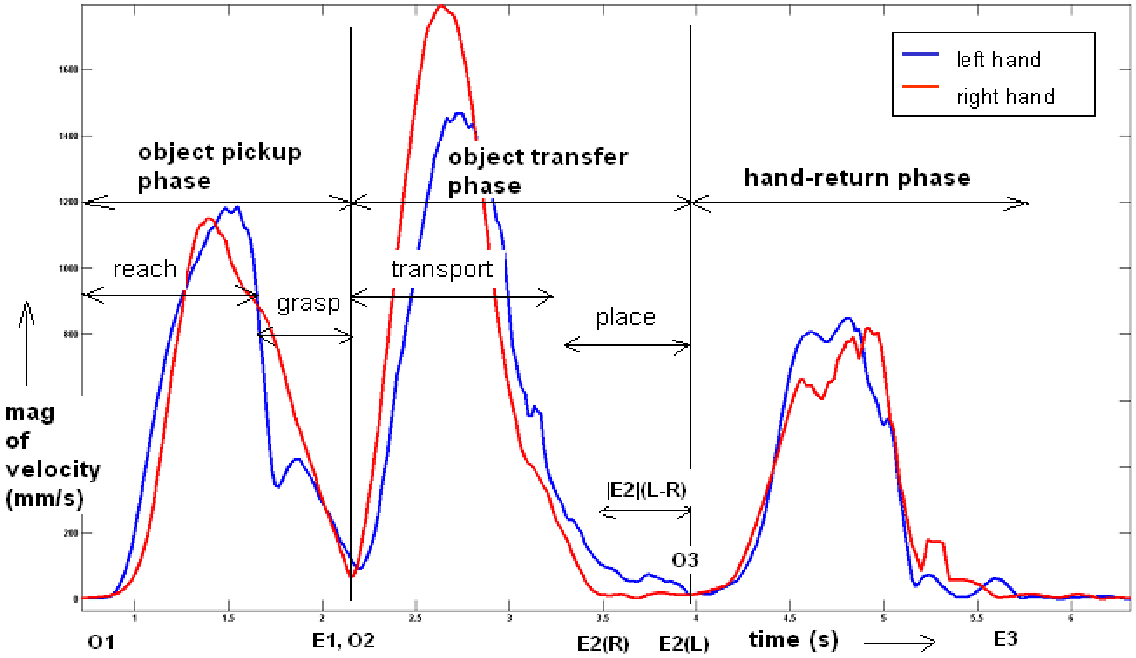
- O3 (Onset of hand-return phase) was defined as the first occurrence of velocity greater than 5 mm/sec, after E2.

- E3 (End of hand-return phase) was determined as the first instant at the end of the return phase when the velocity was less than 5mm/sec.

O1 was also the movement onset time and E3 marked the end of movement. The onset and end times of each phase (O1, E1, O2, E2, O3, E3) were determined for the left and right hands in each trial. For each subject, the absolute difference between onset times of left and right hands and that between the end times of left and right hands for each phase ($|O_1|_{L\text{-}R}$, $|O_2|_{L\text{-}R}$, $|O_3|_{L\text{-}R}$, $|E_1|_{L\text{-}R}$, $|E_2|_{L\text{-}R}$, $|E_3|_{L\text{-}R}$) were determined in each trial. The differences were averaged over the three repetitions in each condition.

Phases of movement in a symmetric bimanual task

(30 mm diameter cylindrical objects picked up from LL and moved to targets of diameter 30 mm, placed 200 mm apart)



O1 – Onset of object pickup phase (Movement Onset), E1 – End of object pickup phase, O2 – Onset of object transfer phase, E2 – End of object transfer phase, O3 – Onset of hand-return phase, E3 – End of hand-return phase (End of Movement)

Fig. 1.5: Typical velocity profiles indicating occurrence of the different phases of a symmetric bimanual task

1.5.3. Results

All movements were found to be multi-phasic, and the phases were consistent across subjects and test conditions. Table 1.1 represents the mean of the differences of one subject for object pickup locations RR, LL and CC and target conditions C1 through C4, for both objects Ob1 and Ob2. The RL condition is not included in this analysis and will be presented separately. Target and object size conditions were believed to affect the precision of the placements and thus influence the task's visual demand. Hence, based on the object size, target size and distance between target locations, 8 levels of task demand (actually visual demand) were defined. While an increase in the distance between target locations caused an increase in the demand of the bimanual task, a decrease in object size and/or target size also increased task demand. Although the exact mathematical relationship has not yet been determined, an index of task demand called the Task Demand Index (TDI) is defined as a generic function of the following factors:

TDI = f (Distance between target locations, object size, target size)

Hence, target condition C2 for Ob1 (object diameter = 30 mm, target diameter = 30 mm, distance between targets = 200 mm) was the condition with highest task demand TDI 1, and target condition C3 for Ob2 (object diameter = 60 mm, target diameter = 120 mm, distance between targets = 30 mm) corresponded to the lowest task demand, TDI 8. Refer to table 1.1 for the definition of the 8 demand levels (TDI 1 – TDI 8).

Object-pickup and Hand-return phases

The difference in onset times of the object pickup phase of the left and right hands ($|O_1|_{L\text{-}R}$) was of the order of 2-4 frames on an average, which translated to a lag of 33-66 ms for a 60 Hz sampling frequency. Similar trends were observed for onset of hand-return phase ($|O_3|_{L\text{-}R}$). The difference in end times of the object-pickup phase ($|E_1|_{L\text{-}R}$) and the hand-return phase ($|E_3|_{L\text{-}R}$) also averaged around the same 33-66 ms. In both these phases, although the time lag between the right and left hands was only of the order of a few ms at both the onset and end of each phase, the left always preceded the right hand.

Object transfer phase

The onset of the object transfer phase ($|O_2|_{L\text{-}R}$) was also synchronized to about the same order for the right and left hands. However, at the end of the object transfer phase, the time lag between left and right hands ($|E_2|_{L\text{-}R}$) was found to vary from a minimum of 33 ms to a maximum of 733 ms. At the end of the transfer phase, precedence of one hand over the other did not exhibit a consistent pattern. No specific pattern in the variation or any factor(s) could indicate a specific preference of one hand's precedence over the other in any particular trial. Thus it may be concluded that one hand's precedence in placing the object on the target location, with respect to the other hand, was random in the context of our experiment. However, online monitoring of the point of gaze from the left eye indicated that the subject always foveated the pair of target locations sequentially, one after the other. Further, this sequence correlated with that of the hand movements at the end of the object transfer phase. In the case of the more significant place-phase lags ($|E_2|_{LR}$), when one hand finished its placement, and was waiting for the other hand to complete its task, it hovered at the target location until the other hand also became free and the onset of the hand-return phases of the two hands was synchronized.

Significant effects

An ANOVA was applied to the data presented in Table 1.1 to determine whether the object pickup location had a significant effect on the place-phase time lag between the two hands ($|E_2|_{L-R}$). No main effects or interactions of object pickup locations reached significance ($p>0.05$) for any of the movement time differences. The influence of task demand on onset and end time differences of pickup and hand-return phases ($|O_1|_{L-R}$, $|E_1|_{L-R}$, $|O_3|_{L-R}$, $|E_3|_{L-R}$) was also not significant ($p>0.05$). However, task demand (a combination of object size, target size and distance of separation between target locations) was found to significantly affect the place-phase time lag between the 2 hands, i.e. the difference in end times of the object transfer phase $|E_2|_{L-R.}$ Since the object pickup locations (RR, LL, CC) did not significantly affect the time differences, the mean of all trials under each target condition was calculated and the mean place-phase time lags have been plotted as a function of task demand index (TDI) in fig 1.6.

RL series of trials

When one object was on the right table and other on the left table, the object pickup phases were not synchronized. After one object was picked up (order of pickup being random), it was transported to a ‘neutral’ position (near the sagittal plane), and the hand hovered there, until the other object was picked up with the second hand and brought to a similar position. Thus, an additional intermediate transfer phase was observed, in which one hand was hovering, while vision was directed to the other hand. At the end of this intermediate phase, when both hands had completed pickups and reached their ‘neutral’ positions, a final object transfer phase was initiated synchronously for both hands. From that point onwards, the time lags and velocity profiles were similar to those of the RR, LL and CC trials.

Table 1.1: Mean of difference between onset times of left and right hands and end times of left and right hands of each phase for different object origin positions and target conditions

Obj diameter = 30mm	C1 (target diameter = 30 mm) (dist betn targets = 30mm) TDI 2						C2 (target diameter = 30 mm) (dist betn targets = 200 mm) TDI 1					
	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$
RR	33	33	33	300	16	50	66	33	33	683	50	33
LL	33	66	66	333	33	16	33	16	16	516	33	33
CC	16	33	33	433	33	50	33	66	50	733	33	66
Obj diameter = 60mm	C1 (target diameter = 60 mm) (dist betn targets = 30mm) TDI 6						C2 (target diameter = 60 mm) (dist betn targets = 200 mm) TDI 5					
	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$
RR	50	16	16	66	50	33	66	50	50	83	33	33
LL	33	50	50	83	33	33	16	50	50	66	16	50
CC	16	33	33	66	16	50	66	33	33	66	50	33

Obj diameter = 30mm	C3 (target diameter = 60 mm) (dist betn targets = 30mm) TDI 4						C4 (target diameter = 60 mm) (dist betn targets = 200mm) TDI 3					
	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$
RR	50	33	33	100	33	50	66	16	16	100	16	66
LL	33	16	16	83	50	33	33	50	50	116	50	33
CC	16	33	33	83	33	66	16	50	50	100	66	33
Obj diameter = 60mm	C3 (target diameter =120 mm) (dist betn targets = 30mm) TDI 8						C4 (target diameter =120 mm) (dist betn targets = 200mm) TDI 7					
	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$	$\|O_1\|_{L-R}$	$\|E_1\|_{L-R}$	$\|O_2\|_{L-R}$	$\|E_2\|_{L-R}$	$\|O_3\|_{L-R}$	$\|E_3\|_{L-R}$
RR	50	33	33	83	16	50	66	16	16	33	16	50
LL	33	50	50	66	50	33	33	50	50	50	16	66
CC	16	50	50	33	33	50	66	16	16	66	33	33

Time values are in milliseconds

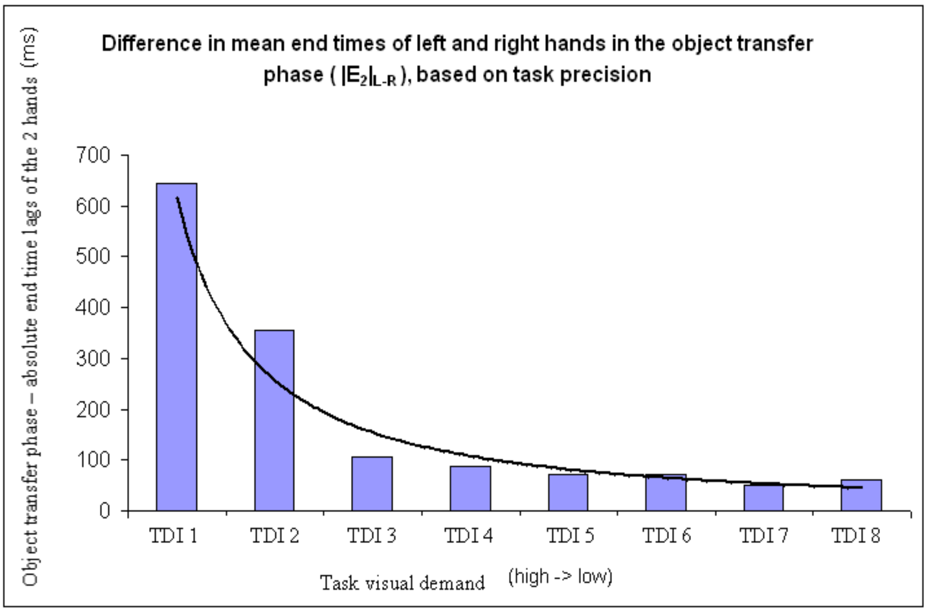


Fig. 1.6: Absolute place-phase lags between left and right hands for different task demands

1.5.4. Discussion

When both objects to be transferred were within the subject's initial visual field, movements were multi-phasic and the onset of each phase (object pickup, transfer and hand-return) was synchronized between the left and right hands. The end of the pickup phase, which coincided with the beginning of the transfer phase, was also synchronized. The end of the hand-return phase was also synchronized. During the transfer phase, although the left and right hand motions were initiated simultaneously, they did not always end together. The extent to which the placement of objects on targets locations occurred in parallel for the right and left hands was a function of the task precision demand. The transfer phase ended synchronously for targets requiring low precision, but the time lag between the right and left hand movements increased as the task demand was increased, causing a ‘sequential termination’ of the transfer phase. However, irrespective of whether the transfer phases of the two hands ended simultaneously or not, the start of the next hand-return phase was synchronized between the two hand movements. One hand, even if it completed the transfer task earlier than the other, waited at the target, such that the initiation of the hand-return phase could be synchronized.

When the object pickup locations of the two hand transfers were not within the subject's initial visual field, after picking up one object, that hand hovered or waited at an intermediate location for the other hand's object also to be picked up, and the subsequent transfers towards their respective target locations were initiated synchronously. During the final stages of the transfer phase, similar to cases in which the objects were both picked up simultaneously, the movement termination of one hand with respect to the other depended on the precision requirement at the target locations. Irrespective of the pattern of movement terminations of the transfer phases, the hand-return phases were initiated synchronously, and also terminated synchronously.

Thus, movements seem to be organized in functionally multiple phases (phases of sub-tasks), such as 'object-pickup', 'transfer' and 'hand-return' phases. Our observations seem to indicate a strong preference for initiating, and maintaining synchronous movements of the two hands to the maximum possible extent. This tendency to synchronize the movements of the two hands seems to be re-initiated at every phase of the movement. Once initiated synchronously, the movements continue in parallel all the way to termination during the object-pickup and hand-return phases. However, during the transfer phases when the precision requirement at the target is high, the two movements break out of synchrony, indicating that the tendency to synchronously couple the two hand movements may operate within certain constraints imposed by resource-limits (limitation of visual feedback).

This study raises the interesting question as to whether coordination of the two hand movements is pre-planned such that a specific pattern of task-dependent coupling is expected between the two movements, or whether the observed patterns of coordination emerge automatically, while the system solves the problem of resource allocation, taking into account the information flow at different level, built-in feedback mechanisms and system constraints.

1.6. Dissertation Organization

The data from the pilot study indicated that the most interesting patterns of coordination arose from the transfer phases, and that the visual demands of the object-pickup and hand-return phases were not high enough to force asymmetry in hand movements. Consequently bimanual 'place' tasks with only the transfer phase were investigated in the main study in order to understand how visual feedback affected the timing and coordination of movement kinematics between the two hands, what specific eye-hand coordination strategies that emerge to fulfill the specific task constraints, and to develop a general bimanual reach control model. Chapter 2 discusses the temporal characteristics of movements in symmetric bimanual tasks (task demand on both left and right hands are the same). Chapter 3 discusses the spatial aspects of eye-hand coordination in movements to symmetric bimanual targets. Chapter 4 describes the spatio-temporal properties of visuomotor coordination in bimanual movements to asymmetric tasks (task demand varied between the left and right hands). Chapter 5 summarizes all the empirical results in a common framework and describes a control model that can simulate key aspects of the behaviors observed in chapters 2, 3 and 4. Chapter 6 discusses the key contributions of this dissertation, lists some of the unsolved challenges and the scope and direction for future work.

CHAPTER 2

EYE-HAND COORDINATION IN SYMMETRIC BIMANUAL TASKS: TEMPORAL ASPECTS

2.1. Introduction

Most skilled manual activities in humans involve the use of both hands. A number of day-to-day activities require separate but coordinated movements of the two hands. For example, fetching a glass with one hand, a jug with another, and filling the glass with water from the jug. This remarkable faculty to produce coherent actions by coordinating both limbs to achieve their individual goals, or a common goal, forms an integral part of our routine behavior. Although the processes underlying single-limb movements have been studied extensively, the neural mechanisms governing inter-limb coordination have received relatively little attention.

The spatio-temporal properties of bimanual movements indicate strong interactions between the left and right limbs (Swinnen 2002) and a number of bimanual studies have reported temporal synchrony in the movements of the two hands. For example, Keele (1986) observed that even while participants were not explicitly instructed to synchronize their hands during bimanual aiming tasks, nevertheless, they tended to do so. Movement initiation and duration were also found to be closely synchronized. In a study on bimanual prehension, Jeannerod (1984) found that in addition to movement onset and duration synchronization, the timing of maximum hand velocity and maximum grip aperture were also similar for each hand. The tendency to synchronize the two hands has also been observed in tasks of mixed difficulty (Kelso et al. 1979; 1983). Kelso reported that Fitts law was violated in bimanual movements when aiming to targets of different indices of difficulty. He observed that the hand reaching to the difficult target took less time than it would, if the other hand was also reaching to a difficult target, whereas the hand reaching to the easy target took more time than it would, if the other hand was also reaching to an easy target.

Although a basic tendency to synchronize the two hands temporally has been established by a number of such studies (Kelso et al. 1979; 1983, Jeannerod 1984; Jackson et al. 1999, Diedrichsen et al. 2001), bimanual aiming and prehension tasks with relatively higher precision requirements have also been found to yield asynchronous coordinative timing, suggesting that temporal synchrony/asynchrony between the two limb movements is context dependent (Balakrishnan et al. 2002).

A recent investigation of coordination in bimanual prehension tasks in which the two hands reached to grasp two objects showed that differences in distances of the two targets yielded asynchronous timing, as expected from normal unimanual movements to two targets at different distances (Bingham et al. 2009). The magnitude of asynchrony was observed to increase with increase in task difficulty. Furthermore, even when task difficulties and distances of movements were the same, although the movements were temporally synchronized during the initial acceleration phases (until peak velocities of transport phases), it was observed that the hands arrived at the targets at different times. It was hypothesized that this asynchrony in the terminal phases of movements was due to the need for each hand to be guided visually to its target. Since two targets separated sufficiently cannot be fixated simultaneously, this asynchrony was hypothesized to be driven by the high perceptual demand of each task. In a similar reach-to-grasp movement study, Mason et al. (2008) also inferred that perceptual factors mediated the temporal coordination during bimanual movements. Furthermore, Balakrishnan et al. (2002) observed that in bimanual tracking tasks, even symmetric bimanual object manipulations (identical task roles for each hand) were not always performed synchronously.

This hypothesis on the importance of perceptual information to bimanual coordination is supported by the study of eye movements associated with bimanual aiming tasks, in which participants were observed to fixate on one target to adjust the spatial end-point error of one hand and then shift to the other target for the same purpose (Riek at al. 2003). The importance of visual acquisition of spatial information to understanding movement kinematics and coordination is further supported by their observation of “hover” phases at the end of the initial transport phases of movements, where one hand hovers at the target, waiting for the other hand to be spatially positioned.

Although the individual task difficulties have been manipulated systematically by varying object sizes as well as movement distances, the extent to which the two separate task demands can be visually integrated, based on different degrees of separation in the visual field, has not been specifically investigated. In the context of high precision tasks, as the spatial resolution of the retina is highest in the fovea and low at the periphery, the accuracy of visual information degrades with the eccentricity from the foveal line of sight (Paillard & Amblard 1985; Bock 1993). Hence, a person’s capacity to obtain visual information from the environment is maximal when gaze is directed at the target, and the accuracy of information perceived drops with increase in target eccentricity from the line of sight. Thus, in a bimanual task, the quality of peripheral vision and its ability to provide visual information about the target becomes crucial in determining whether, when presented with two separate task goals, the dual task constraints can be met simultaneously. The distance of separation of the two target stimuli would affect how well visual cues signaling the position of each hand relative to its specific target could be integrated.

Although the decreasing quality of visual information with increasing spatial eccentricity suggests the importance of eye-movements to obtaining visual information about the target in order to make movement corrections, recently Bruyn et al. (2009) questioned the role of overt vs. covert shifts of visual attention in the performance of bimanual reach-to-grasp movements. Their results indicated that temporal coordination of both the transport and grasp phases did not vary significantly between natural and constrained-vision cases. This is in agreement with observations made by Diedrichsen et al. (2004), who reported that overt eye-movements were not always necessary for online corrections of bimanual movements, and observed movement corrections even when subjects shifted visual attention covertly between targets. These studies (Bingham et al. 2008, Mason et al. 2008, Bruyn et al. 2009, Riek at al. 2003, Diedrichsen et al. 2004) stress the importance of investigating the underlying eye-hand coordination mechanisms in order to understand how the actions of the two hands are temporally coordinated, when presented with two separate goals.

Another important factor while investigating eye-hand coordination mechanisms may be to recognize the role of inherent asymmetries of the left and right hand subsystems in bimanual coordination. Riek at al. (2003) have noted from the patterns of eye movements recorded, that when right-handed participants make bimanual aiming movements, they tend to favor fixations to the left-hand target first, but that this effect depended on target size. When target sizes of the right and left hands were different, and when the left hand was moving to the smaller of the pair of targets, there was a larger tendency for a first left-target fixation than when the left hand was moving to the larger of the pair of targets. These authors suggest that this could be the effect of an interaction between the visual system and the manual asymmetries of the right and left (dominant and non-dominant) hands. Bingham et al. (2008) observed that when target distances were different, the order of asynchrony was such that people reached to the nearer target first. When target distances were the same, although asynchrony was still present, the ordering of hands was largely random.

Although the source of left-right asymmetry is debated, various studies have confirmed that there is a qualitative difference in the performance of the two limbs. It is now well-known that the right hand performs with better accuracy and consistency in right-handed individuals while performing a manual aiming task (Elliot et al. 1995). Flower’s feedback processing hypothesis (1975) predicts that the differences between the left and right hand performances are due to difference in the sensory or feedback control of movements, rather than motor function. A recent model proposed by Adamo and Martin (2009) shows that an asymmetry in position sense between the right and left hands could result from a difference in the gain of the respective proprioceptive sensory-motor loops. Other studies also suggest asymmetries in information processing and/or movement control modes (Sainburg and Kalakanis 2000; Sainburg 2002; Sainburg and Schaefer 2004; Wang and Sainburg 2004). The specific contribution of such asymmetries to bimanual performance still remains an open question.

In this study, the role of vision in temporal coordination of symmetric bimanual tasks (identical task difficulties for each hand) was investigated by systematically varying individual task difficulty of each hand, as well as varying the distance of separation between the two targets. The task consisted of bimanual transfers of two objects, followed by their placements onto their respective targets. While the individual task difficulty was manipulated by varying the object sizes and target tolerances, the distance of separation between the two tasks was set at two levels such that: (i) while any one target was fixated, the other target would be within the field of vision. (ii) while any one target was fixated, the other target would be outside the field of vision. Although the distance “between” targets was manipulated, the two hands always had to move the same distance to reach their respective targets.

The individual task difficulties and the different extents of task overlap (in the visual field) were expected to interact to yield both synchronous and asynchronous timing of hand movements, and also different eye-hand coordination patterns. A differentiation of eye-hand coordination patterns in this context was attempted, in order to understand how separate actions with individual goals are temporally coordinated when relying on a feedback common to both systems – vision.

2.2. Methods

Six right-handed individuals, four male and two female, aged 20-30 years, participated in this experiment as volunteers. All participants were naïve to the purpose of the experiment, with no prior experience at the specific tasks. They had normal vision and were free from neurological and musculo-skeletal disorders. The experiment was approved by the Institutional Review Board of the University of Michigan and all participants signed an informed consent form.

2.2.1. Experimental setup

The experimental task consisted of moving a pair of objects, one with each hand, from their respective initial positions to specified target locations. Three pairs of light weight cylindrical objects, of height 120 mm, and diameters 8mm (obj 1), 18 mm (obj 2), 44 mm (obj 3) were used in the study. The weights of the objects were 8 gm, 22 gm and 60 gm respectively. The target diameter was defined with respect to the object diameter. For each object, the following three target tolerances were defined (Fig 2.1):

1. Target diameter = object diameter + 0 mm (tol1)
2. Target diameter = object diameter + 15 mm (tol2)
3. Target diameter = object diameter + 45 mm (tol3)

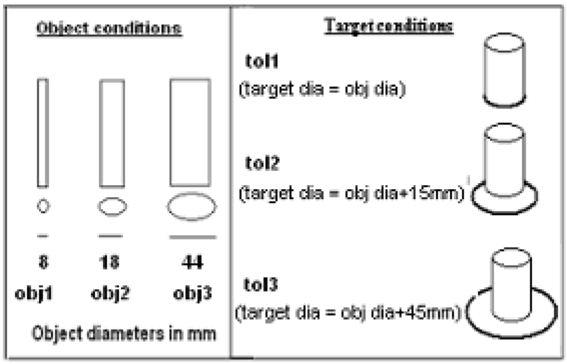


Fig. 2.1: Object and target conditions

Object size, target tolerance and the distance of separation between the pair of targets were chosen to be the task design variables. Distance between the pair of targets, defined by the distance between the two closest points on the target circles, was either 30 mm or 200 mm. The object-to-target distance was set at 400 mm for all trials, as shown in Fig 2.2.

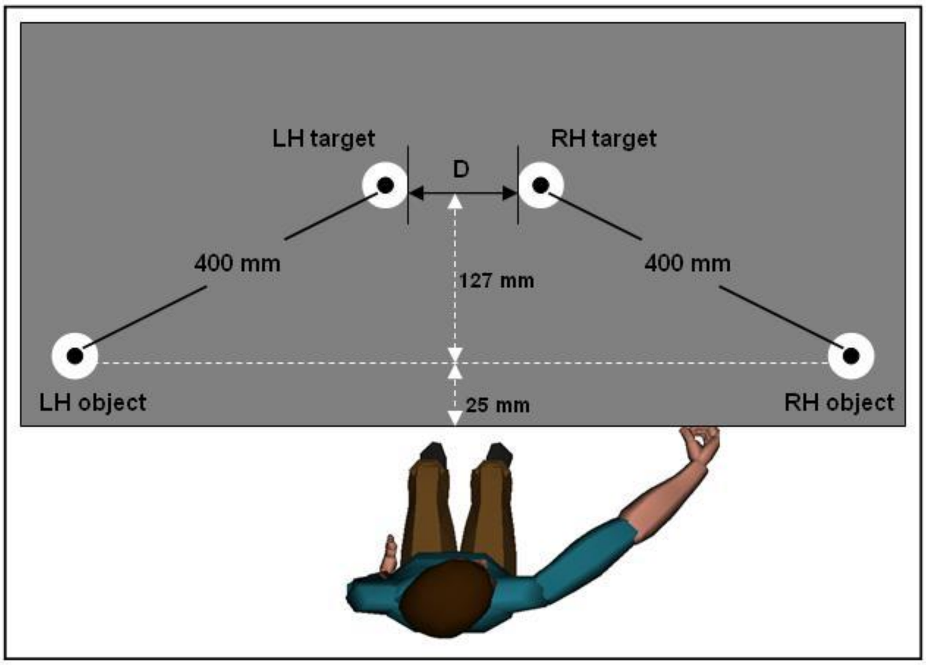


Fig. 2.2: Experimental setup showing the object and target locations on LCD screen (Note: D indicates distance between targets)

The initial object and final target locations were displayed as images on a 52” flat-screen TV placed horizontally at each subject’s elbow height (Fig 2.2). Subjects were seated in front of the TV such that the screen centerline was aligned with their mid-sagittal plane. The near edge of the screen was placed 250 mm away from the participant’s pelvis. The screen‘s aspect ratio of 16/9 translated to a frame resolution of 1920 X 1080. At the initial locations, the centers of objects were 25 mm away from the near-edge of the screen and ~ (380 + 0.5*inter-target distance + 0.5*target tolerance)mm from the mid-sagittal plane, while the target centers were positioned along a horizontal line that was 127 mm away from the line joining the initial object center locations. The centerline of the screen was used as the axis of symmetry to place the objects and targets. All trials were designed such that any hand’s transfer task consisted of moving objects from initial to final locations, without either hand crossing the mid-sagittal plane. An image file, based on specifications for the object and target sizes and their respective locations, was displayed on the monitor for each task condition. The sequence of image files was randomized and played using a software interface to generate each trial during the experiment.

2.2.2. Movement recording

An eight-camera Qualisys® motion capture system was used to record kinematic data sampled at 60 Hz. Passive, reflective markers were placed on selected body landmarks to record the subject’s hands, arms, torso and head movements as illustrated in Fig 2.3. Markers were placed on important body landmarks: head (3), left and right shoulders (2), elbows (2), wrists (2), sternum (3) and pelvis (2). Eye movements were recorded simultaneously using a head mounted eye tracking system (ASL Eye Trac 6.0). The direction and point of gaze were also monitored on line on a video screen (Fig 2.3). Both gaze and body movement signals were synchronized and recorded at 60 Hz. Video images of all trials were recorded using a JVCGR-DX97 video camera that was also synchronized with the movement data recording system.

Gaze data was obtained using a two-step calibration procedure. The first step was to calibrate the eye-in-head position using the standard 9 point calibration procedure provided by ASL. During this procedure, the head position was fixed using a bite-bar attached to a fixed frame. The calibration targets were presented on the actual work plane on the LCD screen surface. The next step was to calibrate the eye-in-space (gaze) orientation. The subject was asked to fixate five points sequentially while the head was free to move. The eye tracker measured the subject's eye-in-head signal for each target, while head position was simultaneously recorded using the motion capture system, to obtain the head-in-space signal. The spatial coordinates of each target were computed using the motion capture system. These datasets were combined to develop an offline calibration procedure to obtain gaze orientation (eye-in-space signal). Thus, to analyze gaze-hand coordination in a common frame of reference, the data pertaining to the line of sight was projected to the work plane defined in the real world coordinates of the motion capture system.

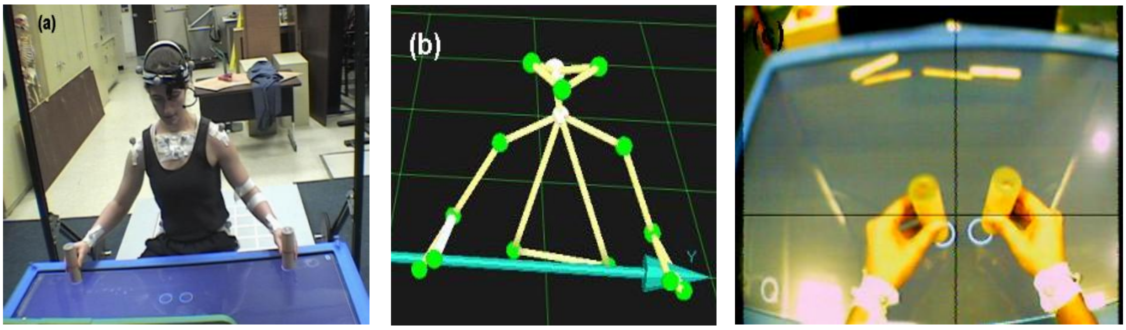


Fig. 2.3: (a) Motion capture and eye-tracker systems setup **(b)** Body linkage system **(c)** Example of a scene from the video camera mounted on the eye tracker: cross hairs indicate the point of gaze

2.2.3. Procedure

Subjects were instructed to move a pair of objects, one with their left and the other with their right hands, from their respective initial positions to specified target locations. The left hand always picked the object on the left and moved it to the left target location, and vice versa for the right, i.e., the task did not require any crossing over of the two hands. No explicit instruction was provided to the subject about the expected sequence of movements and no constraints were imposed on speed of movements either.

The subjects started each trial with the objects already grasped in their hands, and the eyes fixating a target placed in the mid-sagittal plane at eye level. This initial eye-position was standardized so that the quality of visual information about the targets was the same for all subjects at the start of each trial and the subject's first gaze shift during the trial could be clearly recorded. On receiving the cue to start, subjects transferred the objects to the target locations, and held them there until the end of the trial without changing hand positions, but gaze was returned to the initial target fixation, after the end of hand movements. Once the transfer task was complete, the subjects continued to hold the objects at the target position until the end of the trial. Kinematic parameters were defined to identify the end of hand movements in each trial. For the gaze data, returning the gaze to the initial-home position identified the end of gaze movements in each trial. A multi-finger pinch grasp was used to hold all objects. Thumbprints were placed on all objects to standardize the grip locations. Movement speed was not specifically constrained, and subjects were asked to move at a comfortable pace to complete the task. The only constraint imposed on task-performance was zero error tolerance in the accuracy of positioning.

Since the pilot studies indicated the development of consistent eye-hand coordination strategies with learning, experimental data collection was initiated after 100 practice/learning trials. The set of 100 practice trials were picked randomly from the actual experiment trials and the subjects were not aware that these practice trials were to be excluded from the analysis. Each condition was repeated three times during the experiment trials. All conditions were randomized and inter-trial intervals were of approximately 15 seconds. Before each trial, the subject was allowed to fixate the locations of the objects and the targets (no gaze limitations). If the accuracy constraints were not met in a trial, it was repeated at the end of the experiment.

For trials in which the target size was larger than the object size, the objects had only to be placed within the limits of the target area and did not have to be centered. The objects had to be moved and brought in vertically. The participants were not allowed maneuvers such as pivoting one end of the object at an angle and rolling it in to the target zone, or sliding the objects on the surface of the screen. Adjustments or corrections were not allowed after the object made contact with the surface. Subjects were also instructed to refrain from bracing/supporting their arms on any surface.

2.2.4. Experimental design

Object size (8, 18 and 44 mm), target tolerance (0, 15 and 45 mm) and the distance between targets (30 and 200 mm) were the independent variables, which yielded a 3X3X2 mixed level factorial design with three repeated measures. Although all three parameters were varied, they were set at the same level for each hand within a trial, to ensure symmetric task constraints between the two hands. Thus a total of 54 trials (18 conditions X 3 repetitions) were recorded for each participant. The labeling convention adopted to identify the trial type was:

"LH object – LH target tolerance – distance between targets – RH target tolerance – RH object"

According to this convention, a trial of type "8-15-200-15-8" means that LH and RH object sizes are 8mm, target tolerances are 15mm (i.e. each target diameter is 23mm), and the distance between the two targets is 200mm.

2.2.5. Data analysis

The three dimensional data from the motion capture system was filtered using a second-order, low-pass Butterworth filter with a cut-off frequency of 6 Hz. The kinematic data from the markers placed on the wrists were used to calculate the onset and end times of movements. Movement onset corresponded to the first instant at which the magnitude of tangential velocity of the wrist marker exceeded 5 mm/sec. The end of movements was defined as the first instant after the occurrence of peak velocity, at which the object came in contact with the LCD screen surface (observed from synchronized video recordings of the trials), and the magnitude of tangential velocity of the wrist marker fell below 5mm/sec. This dual constraint was used to define the end of movements since it was observed that in some trials, when one hand entered its final task-completion phase, the other hand would hover at an intermediate location short of its target. The hand velocity fell below the defined threshold of 5mm/sec in such cases, because the velocity condition alone was insufficient to define the end of movements, and the constraint of hand reaching the target was added.

The raw eye-position data was converted to a series of fixation events by EyeNal, the offline data analysis program provided by Applied Systems Laboratory (ASL) for processing eye movement information. The EyeNal program used a moving window technique with the following parameters to calculate fixations: A fixation was started when the standard deviation of 6 consecutive samples of raw eye-position data (corresponding to about 100 ms) fell within 0.5 degrees of visual angle and was ended when 3 consecutive samples fell outside of 1 degree. The fixation duration was calculated as the amount of time between the first data sample of the starting samples and the sample immediately preceding the first of the ending samples. The fixation position was calculated as the mean position of all samples that fell within a visual angle of 1.5 degrees. Blinks (pupil losses up to a maximum of 200 ms) were ignored and did not terminate fixations.

The resolution of the eye tracker was less than a degree. However, since the work plane was not always normal to the head-mounted eye tracker, the actual resolution obtained was less than that indicated in the specifications. The resolution was assumed to be of the order of ~1 degree since the calibration plane was almost a meter away from the subject's eye, and this translated to a spatial error of ~ 17 mm. As the target sizes were of the same order of magnitude, gaze orientation was only used to define landmark zones corresponding to one target or the other, and not to identify the exact point of foveation at any given point of time. Landmark zones were defined as concentric circles of diametric tolerance of 10 mm about the respective targets. The coordination of gaze and hand actions was described in terms of the temporal coordination between gaze shifts entering and exiting landmark zones (each hand's target) and the specific kinematic events associated with the hand movements. The maximum distance between the targets in the experiment was only 200 mm, (corresponding to an approximate visual angle of ~12 degrees). Since the data was sampled at 60 Hz, the gaze shift from one target to the other appeared almost instantaneous. The shift was often complete within 1-2 frames of measurement. Hence, in this study, gaze shifts have been assumed to be instantaneous. The foveal field of view was defined to subtend a solid an angle of ~2 degrees about the line of gaze and the peripheral field of view up to 20 degrees (Jeanerrod and Prablanc, 1983).

The difference between the movement onset times of left and right hands (O_{L-R}), the difference between time to peak velocity of left and right hands (P_{L-R}) and the difference between movement termination times of the left and right hands (E_{L-R}) were computed, to determine temporal synchronization/de-synchronization between the two hands. Repeated measures ANOVA analysis, with each trial's object size, target tolerance and distance between targets as between-subjects factors, was used to test significance ($\alpha=0.05$) of different trial conditions on the above described kinematic parameters.

2.3. Results

2.3.1. Onset, peak velocity and end times of hand movements

Typical velocity profiles of the left and right hands of subject 2, in a bimanual trial of type 8-0-30-0-8, are illustrated in fig 2.4. Repeated measures ANOVA results did not show any significant learning effect for any of the dependent measures. Task condition did not have a significant effect on the magnitude of the time lag in movement onset between the two hands ($|O_{L-R}|$). As indicated by Table 2.1, neither the main effects nor the interactions of object size, target tolerance and the inter-target distance had a significant influence on $|O_{L-R}|$.

Similarly, the task conditions also did not significantly affect the magnitude of difference in time to peak velocities of the left and right hand ($|P_{L-R}|$). Task conditions did not significantly affect the order in which the left and right hands started the movements or reached peak velocity. Thus, the task conditions did not significantly affect the sign of time lags in movement onset & time to reach peak velocity ($\boldsymbol{P} > 0.5$).

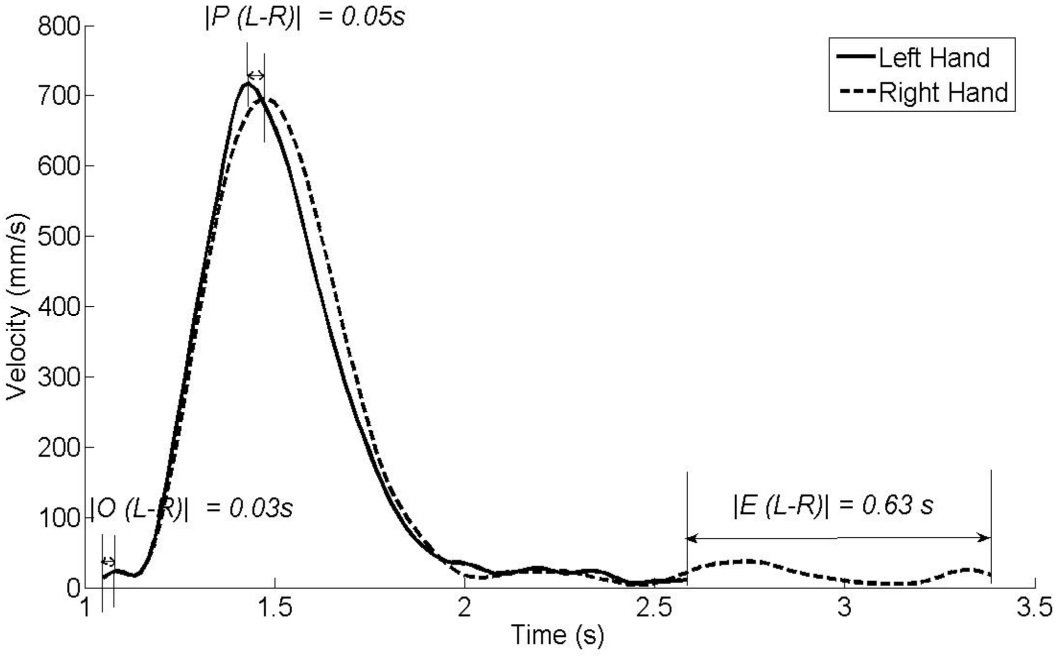


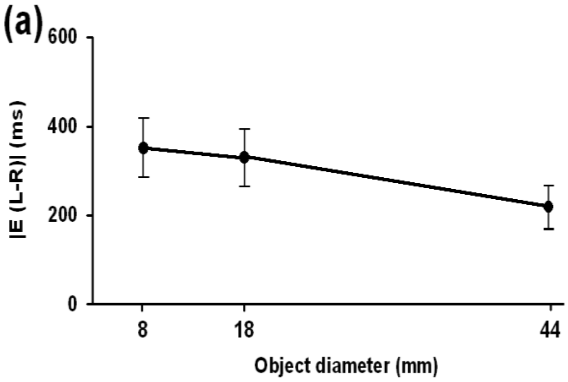
Fig. 2.4: Typical velocity profiles of hands in a bimanual trial of type 8-0-30-0-8

Table 2.1: Repeated Measures ANOVA-effect of task conditions on $|O_{L-R}|$, $|P_{L-R}|$ & $|E_{L-R}|$

General Linear Models (alpha = 0.05)		**$\lvert O_{LR}\rvert$**		**$\lvert P_{L-R}\rvert$**		**$\lvert E_{L-R}\rvert$**	
Factor	**DOF**	**F stat**	**P-value**	**F stat**	**P-value**	**F stat**	**P-value**
Object size	2	1.1	0.34	0.5	0.61	19.2	0
Target tolerance	2	0.24	0.79	0.07	0.93	601.3	0
Distance between targets	1	0.11	0.75	1.7	0.2	101.2	0
Object size*Target tolerance	4	0.47	0.76	0.08	0.99	14.32	0
Object size*Distance between targets	2	0.06	0.94	0.3	0.74	5.01	0.09
Target tolerance*Distance between targets	2	1.29	0.28	0.01	0.99	65.32	0
Object size*Target tolerance*Distance between targets	4	0.5	0.74	0.15	0.96	6.08	0
Error	90						

Since the task conditions did not have a significant effect on time lag in movement onsets and time to peak velocities, the average value of these parameters were calculated by collapsing across all conditions and subjects. The average lag, or average absolute difference in movement onset times between the left and right hands ($|O_{L-R}|$) across all conditions was 28 ± 20 ms. The average absolute difference in times to peak velocity of the left and right hands ($|P_{L-R}|$) across all conditions was 36 ± 31 ms.

However, as observed in Table 2.1, main and interaction effects of task parameters significantly affected the magnitude of difference in end times ($|E_{L-R}|$). The absolute difference between the end times of left and right hand movements decreased with increase in object size and target tolerance and increased with increase in distance between targets. These significant main effects are described in Fig 2.5.



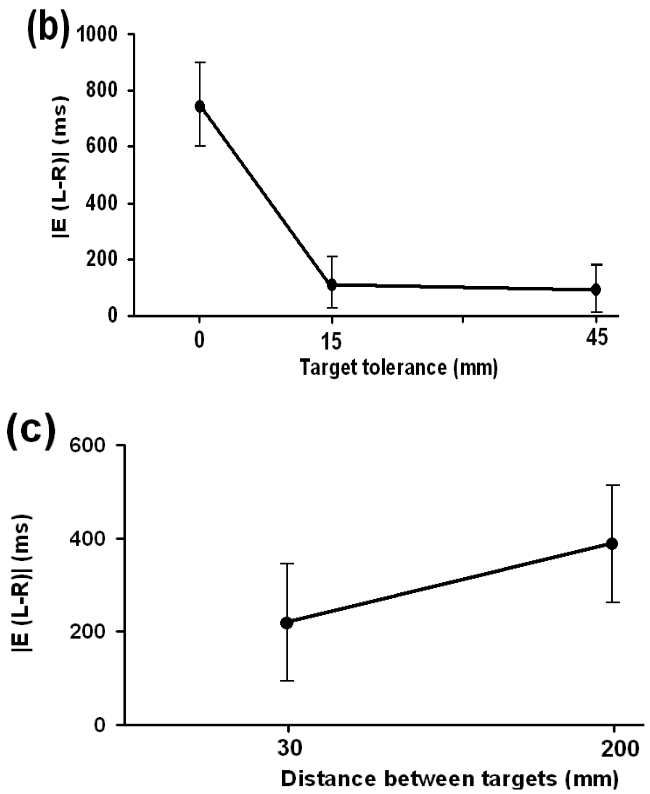


Fig. 2.5: (a, b, c) Main effects plots of object and target size, and distance between targets for $|E_{L-R}|$

Although the main effects of all three factors were significant, Tukey's pair-wise comparisons indicated that varying the object size from 8 to 18mm did not have a significant effect on $|E_{L-R}|$ ($\boldsymbol{P}$=0.14). However, the difference in $|E_{L-R}|$ was significant when object size was changed from 18 to 44mm ($\boldsymbol{P}$=0.0007). Similarly, varying the target tolerance from 0 to 15 mm had a significant effect on $|E_{L-R}|$ ($\boldsymbol{P}$<0.0001). However, varying the target tolerance from 15 to 45 mm did not affect $|E_{L-R}|$ significantly ($\boldsymbol{P}$ = 0.15). Two-way and three-way interactions of object size, target size and distance between targets were also found to be significant, as illustrated in Fig 2.6. From Tukey's pair-wise comparisons of the interaction effects of object size vs. target tolerance, it can be observed that while $|E_{L-R}|$ decreased with increase in object size for the smallest target tolerance (0 mm), it did not change significantly with object size at higher target tolerances. Similarly, from the interaction effects of object size vs. distance between targets in Fig. 2.6b, it can be observed that the increase in $|E_{L-R}|$ with increase in distance between targets was significant for all object sizes. The interaction effects of target tolerance vs. distance between targets (Fig 2.6c) indicate that increase in $|E_{L-R}|$ with increase in distance between targets was highest when the target tolerance was smallest (0mm). $|E_{L\text{-}R}|$ did not vary significantly by changing the distance between targets for higher target tolerances of 15 and 45mm.

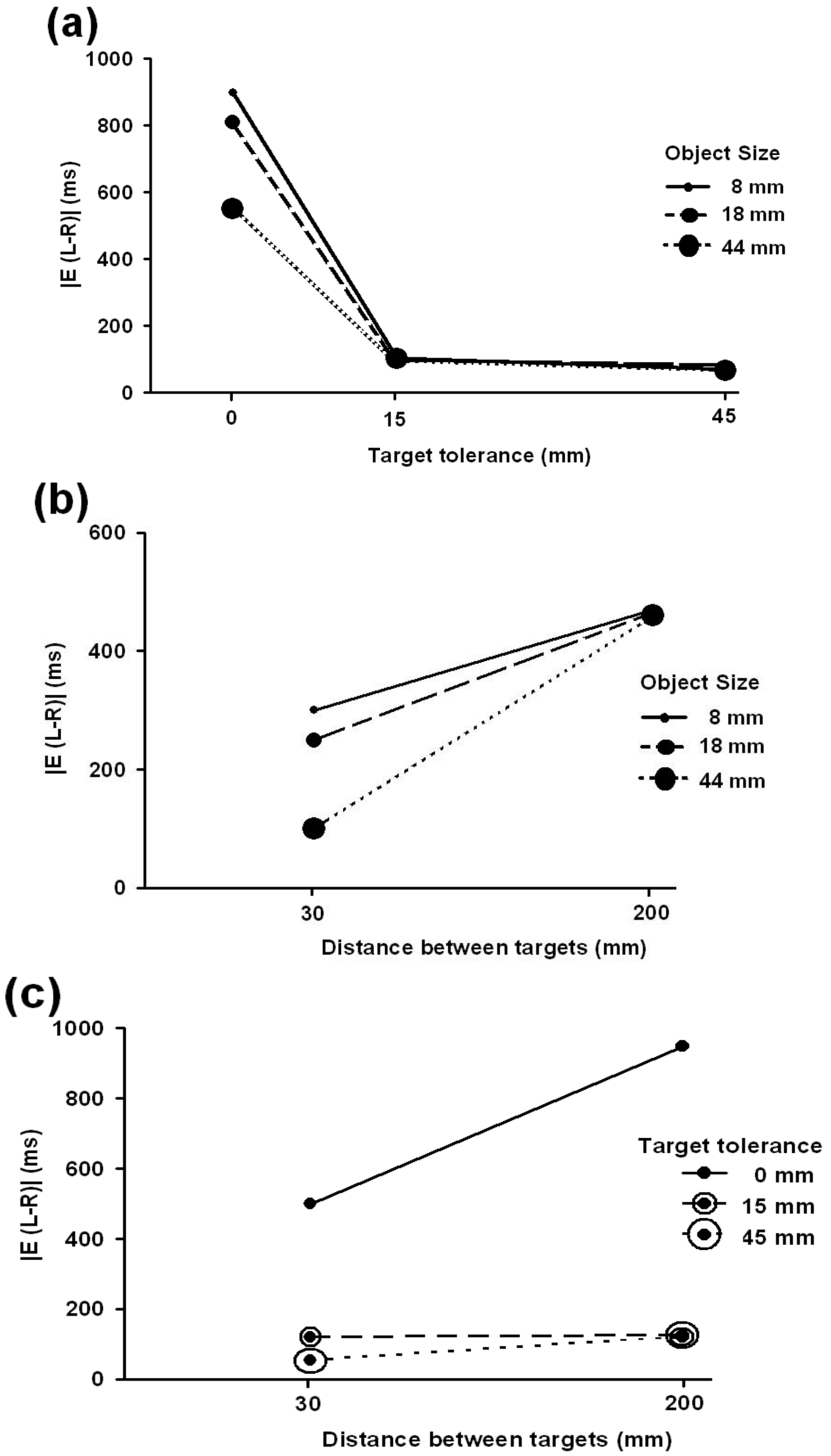


Fig. 2.6: Interaction plots with fitted means of $|E_{L\text{-}R}|$: **(a)** Object size*Target tolerance; **(b)** Object size*Inter-target distance; **(c)** Target tolerance*Inter-target distance

Table 2.2 summarizes the results of Tukey's tests for the two-way interactions of the highest and smallest values of the three factors: object size (ob), target tolerance (tar) and distance between targets (dist).

Thus, although the onset and time to peak velocities of movements were synchronized, at some point of time after the peak velocity was attained, one hand started slowing down/speeding up with respect to the other. Significance of the difference between the end times of the left and right hand movements (de-synchronization) was dependent on task conditions.

Table 2.2: Tukey's pair-wise comparisons of specific interaction effects

Level 1	Level 2	P value
Ob 8mm, tar 0mm	Ob 44mm, tar 0mm	<0.0001
Ob 8mm, tar 45mm	Ob 44mm, tar 45mm	0.9989
Dist 30mm, ob 8mm	Dist 200mm, ob 8mm	0.0002
Dist 30mm, ob 44mm	Dist 200mm, ob 44mm	<0.0001
Dist 30mm, tar 0mm	Dist 200mm, tar 0mm	<0.0001
Dist 30mm, tar 45mm	Dist 200mm, tar 45mm	0.6732

2.3.2. Classification of placement behavior

Based on the absolute difference in end times of left and right hand movements ($|E_{L-R}|$), placement behavior was broadly classified as 'simultaneous' (when $|E_{L-R}| \leq 50$ ms or 3 frames of recording) or 'sequential' (when $|E_{L-R}| \geq 100$ ms). The dependence of the placement behavior on the task variables was investigated using only the two extreme settings of each of the three variables (Table 2.3).

These are designated as low and high settings of each variable for ease of reference:

(i) Object size: 8 mm (low) & 44 mm (high)
(ii) Target tolerance: 0 mm (low) & 45 mm (high)
(iii) Distance between targets: 30 mm (low) & 200 mm (high)

Table 2.3: Dependence of placement strategy on experimental design variables

object size	**target tolerance**	**Distance between targets**	**placement strategy**
low	low	low	sequential
low	low	high	sequential
high	low	high	sequential
high	*low*	*low*	*simultaneous*
low	high	low	simultaneous
low	high	high	simultaneous
high	high	low	simultaneous
high	high	high	simultaneous

2.3.3. Hand precedence in termination phases

In 91% of all trials in which placement was sequential, the left hand preceded the right hand to complete its placement (although there was no significant hand precedence at the start of the movements or at peak velocities). This phenomenon of left hand precedence in sequential trials was not influenced by task condition or inter-subject differences.

2.3.4. Gaze patterns

- Gaze was directed exclusively to one of the two targets while the hands moved.

- In 97% of the sequential trials, gaze shifted only once: It was first directed to the target at which object placement occurred first, then to the other target. In 94% of such trials, gaze was directed first to the left hand target, and then to the right hand target.

- In 89% of the trials in which placement was simultaneous, gaze shifted only once: It was directed first to the left hand target, then to the right hand target.

- The time at which the shift in gaze occurred from one target to another varied with task condition, and different gaze strategies were defined to describe the timing of gaze shifts with respect to hand movement kinematics.

2.3.5. Gaze strategies

The coordination of gaze and hand actions was investigated in terms of the temporal coordination between gaze shifts entering and exiting the target zones and each hand movement’s specific kinematic events.
As illustrated in fig 2.7, four main gaze strategies emerged:

(i) Terminal gaze strategy: Gaze is directed towards one of the targets (target 1) first, and after completion of placement of the corresponding object, moves to the other target (target 2);

(ii) Predictive gaze strategy: Gaze is directed towards target 1 initially, but then redirected to target 2 even before the completion of placement at target 1;

(iii) Intermittent gaze strategy: Gaze is repeatedly switched from one target to another (more than once) during the execution of the bimanual task;

(iv) Selective gaze strategy: Gaze is directed at one of the targets and remains there until the completion of the entire bimanual task when both hands complete their placements.

2.3.6. Dependence of gaze strategies on experimental task conditions

The particular strategy chosen in any trial may depend on task parameters. Hence, the relationship between gaze strategies and task conditions, and its consistency across subjects was investigated using the two extreme settings of each of the three variables as described in the previous section.

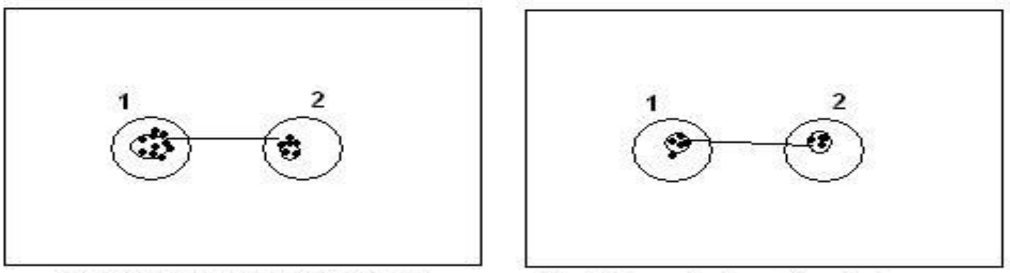
The following relationships were found to be consistent across all subjects:

- For small object size and low target tolerance, irrespective of the distance between targets (types 8-0-30-0-8 and 8-0-200-0-8), terminal gaze strategy was adopted in 98% of the trials.

- For large object size, low target tolerance and low distance between targets (type 44-0-30-0-44), intermittent gaze strategy was adopted in 82% of the trials.

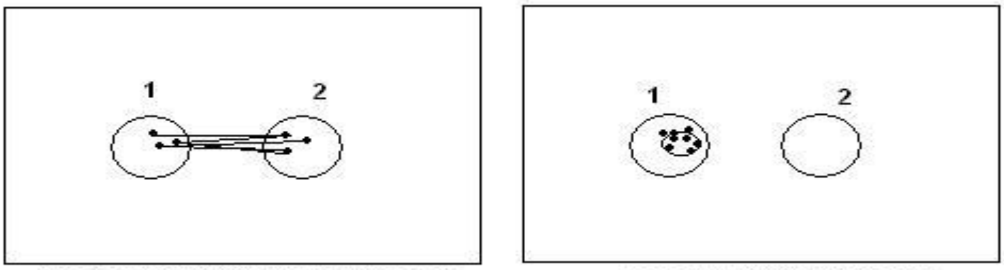
- For high target tolerance and high distance between targets, irrespective of object size (types 8-45-200-45-8 and 44-45-200-45-44), predictive gaze strategy was adopted in 96% of the trials.

- For high target tolerance and low distance between targets, irrespective of object size (types 8-45-30-45-8 and 44-45-30-45-44), selective gaze strategy was adopted in 87% of the trials.



Terminal strategy: 1 final gaze transition from target 1 to 2

Predictive strategy: 1 preliminary gaze transition from target 1 to 2



Intermittent strategy: Multiple gaze transitions between targets

Selective strategy: No gaze transitions between targets

Fig. 2.7: Four different gaze strategies in symmetric bimanual placements

Typical examples of the four different gaze strategies, and corresponding hand movements are illustrated in Fig 8: Gaze is directed to the left hand's target until completion of placement by the left hand and then shifts to right hand's target (Fig 8a); repeated shifts of gaze, or intermittent sampling, from left to right hand targets (Fig 8b); gaze is directed selectively to the left hand's target only, and during that time, the right hand also completes its movement (Fig 8c); gaze is initially directed to the left hand target but shifts to the right target before completion of the left hand placement (Fig 8d).

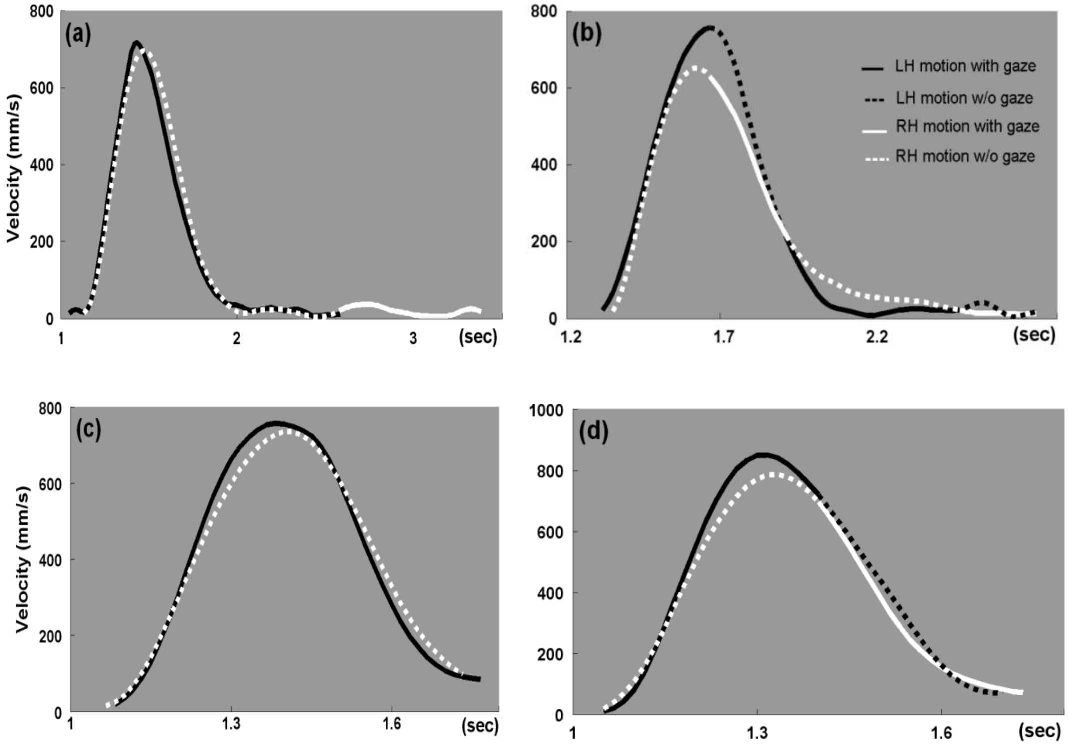


Fig. 2.8: Four different eye-hand coordination strategies (solid lines indicate hand movement when gaze is directed to that target; dotted lines indicate hand movements when gaze is directed to the other target)

(a) A sample 8-0-200-0-8 type bimanual trial, showing velocities of left and right hands, with gaze direction super-imposed, thus illustrating the ‘terminal gaze strategy’

(b) A sample 44-0-30-0-44 type bimanual trial, showing velocities of left and right hands, with gaze direction super-imposed, thus illustrating the ‘intermittent gaze strategy’

(c) A sample 44-45-30-45-44 type bimanual trial, showing velocities of left and right hands, with gaze direction super-imposed, thus illustrating the ‘selective gaze strategy’

(d) A sample 8-45-200-45-8 type bimanual trial, showing velocities of left and right hands, with gaze direction super-imposed, thus illustrating the ‘predictive gaze strategy’

2.3.7. Eye-hand coordination

Gaze and hand-placement strategies are described as a function of task variables in Table 2.4. When target tolerance is high, placement is always simultaneous, using either the selective or predictive gaze strategies. When target tolerance is low, placement is either simultaneous or sequential, depending on object size and distance between targets. The intermittent gaze strategy is used to fixate targets when target tolerance is low, object size is high and distance between targets is low.

Table 2.4: Eye-hand coordination strategies in bimanual tasks

object size	**target tolerance**	**distance between targets**	**placement strategy**	**gaze strategy**
low	low	low	sequential	terminal
low	low	high	sequential	terminal
high	low	high	sequential	terminal
high	low	low	simultaneous	intermittent
low	high	low	simultaneous	selective
high	high	low	simultaneous	selective
low	high	high	simultaneous	predictive
high	high	high	simultaneous	predictive

2.4. Discussion

Although the subjects were not instructed regarding movement synchrony, the movement onsets and time of peak velocities of the two hands were synchronized, as observed in previous studies of bimanual aiming and prehension movements (Kelso 1979, 1983; Jeannerod 1984; Keele 1986; Jackson et al. 1999). However, after the initial temporal coupling, complex patterns of coordination emerged in the terminal phase of the movements of the two hands, as a function of task parameters. This result seems to be in agreement with the hypothesis proposing that the temporal coupling of eye and hand movements vary in a task-dependent manner, especially in high-precision tasks (Swinnen 2002; Bingham et al. 2008, Mason et al. 2008, Bruyn et al. 2009). The task-dependent eye-hand coordination patterns are believed to optimize the useful flow of visual information for the particular task (Fisk and Goodale 1985; Land and Hayhoe 2001; Rossetti et al. 1993; Sailer et al. 2000). Gaze strategies identified in our study, which are associated with the visual requirements of the placement tasks, can be used to interpret the effects of task parameters on placement synchrony at movement termination.

In a recent study on bimanual reach-to-grasp tasks, Bruyn et al. (2009) questioned whether under normal visual conditions participants would direct visual attention towards their hands, the targets they were reaching for, or a combination of both hand and target. In the present study, gaze was directed only to the targets, and not the hands, during the entire movement.

Different gaze patterns emerged during the terminal phases of the hand movements. Johansson et al. (2001) suggested that fixating gaze at particularly task-relevant points in a coordinated sequence allows for periods in which the brain can calculate the geometric relationships between the visual representation of the external world and the proprioceptive internal representation. This may indicate that visual information is used to calibrate proprioception in anticipation of its contribution to movement control of one limb when vision is used for the other, as discussed below.

2.4.1 Eye-hand coordination behavior in terminal phases of place movements

Terminal gaze strategy

When the target tolerance is low (precision is high), irrespective of object size and distance between targets, gaze is directed to one target, the object is placed at that target, and then gaze is redirected to fixate the other target. In such cases, it appears that precise object placement requires visual feedback to guide the hand. This terminal gaze strategy imposes a sequential hand-placement strategy. Neither peripheral visual information nor proprioceptive feedback (or a combination of both) seems to be sufficient to complete the task. This gaze strategy is similar to the eye-movements observed by Riek at al. (2003) during bimanual styli aiming tasks, in which participants were observed to fixate one target, correct the spatial end-point error of the hand and then subsequently fixate the other target to do the same for the other hand.

Since the accuracy of perceived visual information is known to degrade with increased eccentricity from line of sight, this strategy represents a possible trade-off between visual demand of the zero tolerance placement task and target eccentricity (of each target when the other target is being foveated). This strategy is similar to the sequential performance observed in bimanual tracking of a pair of symmetric targets (Balakrishnan et al. 2002, Bingham et al. 2008).

Selective gaze strategy

Although a number of studies have observed synchronous arm movements and investigated the coordination and kinematics of transport and grasp phases (Jackson et al. 1999), the question of whether the quality/quantity of information required for high-precision bimanual tasks involving two separate objects can be acquired, without moving our eyes to fixate each target separately has been raised (Bruyn et al. 2009).

In the present study, when target tolerance is not restrictive, and the distance between targets is small (30 mm) , gaze is directed to only one target, to guide both hands to their respective target positions simultaneously. As the 30mm distance between the pair of targets corresponds to a visual angle of ~ 2 degrees in the tested conditions, fixating one target includes the other within the foveal field of view. The relaxed accuracy demand of the task, in combination with fixation of both targets, allows simultaneous guidance of both hands to their respective targets using the selective gaze strategy. Diedrichsen et al. (2004) reported similar observations in their study of online corrections in bimanual movements. This study reported that overt eye movements (which change the fixation point from one target to another) are not always necessary to obtain the visual information needed to make online corrections during bimanual movements.

Predictive gaze strategy

When target tolerance is not restrictive, and the distance between targets is large (200 mm), although gaze is initially directed to one target, a gaze shift is necessary to obtain visual information about the other target. As the 200 mm distance corresponds to a visual angle of ~ 12 degrees, the second target is outside the foveal field associated with a fixation to the first target. In this context, the insufficient spatial accuracy of the peripheral field of view (Jeannerod et al. 1983) leads to a gaze shift to obtain accurate spatial information to guide the second hand to its target.

A study of the specific point in the movement trajectory, and the time at which such gaze transitions occur, as a function of the task parameters, would help us understand how visual information of the target aids in the planning and execution of movements. Since a voluntary gaze transition “away” from the target while the hand is still moving to the target, is a characteristic of coordination that is seldom observed in single-handed movements, this gaze strategy is particularly valuable to understanding principles of eye-hand coordination.

The kinematics of the hand movements exhibited in both the predictive and selective strategies are almost identical and placements of the left and right hands are simultaneous in both cases. However, the significant difference in gaze strategies: fixation on a single target versus gaze shift before movement completion, suggest a difference in the underlying feedback and coordination mechanisms between the two behavior patterns. This suggests the possibility that two movements exhibiting almost identical kinematics could potentially be controlled by different coordination mechanisms, an issue that has not been specifically investigated in the past, in the context of bimanual aiming/prehension movements.

Since targets are usually coded visually in an extrinsic frame of reference, and movement is thought to be coded in the intrinsic and kinesthetic frames (Soechting & Flanders 1989), sensorimotor transformations are required to reach the visually presented target. Having a proprioceptive reference corresponding to the target locations is believed to greatly reduce errors in the approximation resulting from these sensorimotor transformations (Vindras et al. 1998). Once calibrated to the external space (allocentric frame of reference) with the help of vision, proprioception can continue to provide feedback in the absence of foveal vision (Lackner 2000). As no specific kinematic event could be associated with the switch in gaze orientation between the targets in our experiment, and as the switching times varied with task condition and individuals, the decision criteria used to initiate the gaze switch remain an open question. Nevertheless it may be assumed that an update of the visual map is necessary to calibrate/recalibrate/update the internal representation that allows the prolongation of hand movements using proprioceptive feedback or feed forward control when target vision is no longer available.

Hence, if the permissible error tolerance in the task is smaller than the inherent variability associated with proprioceptive feedback, especially when it involves coordinate transformations from internal to external coordinates, then the system probably uses visual information to re-calibrate proprioception with respect to the external world at periodic intervals. Therefore, if the accuracy demand of the task can be met by using a peripheral source of information, then a gaze transition is probably not required for a recalibration. In zero tolerance conditions, a gaze shift might be required to provide the more accurate visual information.

Intermittent gaze strategy

When large objects are moved to close targets of small tolerance (44-0-30-0-44 type of trials), gaze is switched from one target to the other multiple times. The observation by Wise et al. (1998) that a conspicuous object, when introduced in the visual field attracts the person's attention and causes saccades to it, seems to support the theoretical existence of the intermittent strategy. This pattern of eye-movements may also be indicative of an attempt to avoid collision of the two objects, when they are brought close to one another. However, although this strategy could have been adopted for any tested condition, choice of the intermittent strategy for this specific trial condition is intriguing. This leads us to believe that the problem of bimanual control might have to be recast in terms of what the central nervous system might be trying to optimize.

Overall, the present study investigates the role of task constraints in bimanual performance, by comparing the role of visual feedback across multiple object and target sizes, and target locations. Bimanual coordination and the extent of synchrony affordable in placement tasks seem to be primarily mediated by the availability of visual resources [in accordance with studies by Bingham et al. 2008, Mason et al. 2008], and their likely contribution to the calibration of proprioception. As visual acuity degrades with eccentricity from the line of sight, the relationship between gaze orientation and hand movements seems to reflect a trade-off between accuracy and synchronization. Thus, although there is a tendency to synchronize the movements of the two hands, this synchrony is maintained within some limits of task and resource constraints.

2.4.2. Left-right asymmetry

In most of the bimanual trials in which the left and right hand placements were sequential, the left hand was observed to precede the right hand in placing the object on target. This observation must be associated with the evidence that in a majority of the trials, irrespective of whether placement was simultaneous or sequential and which gaze strategy was used, gaze was directed onto the left hand target first, and remained there, until the time when both hands attained their peak velocities. This implies that in most bimanual trials, except for trials in which the intermittent gaze strategy was used, the line of gaze was on the left hand target at least until a point in the right hand movement's terminal phase. Hence, except for the terminal phase of movements, most part of the right hand movements seem to have been performed with the target in the periphery, while gaze was directed to the left hand target preferentially. In cases of selective gaze strategy, the complete right hand movement is performed with vision directed to the left hand target.

In an earlier study by Riek et al. (2003), right-handed participants making bimanual aiming movements tended to favor fixations to the left-hand target first, but this effect was said to be dependent on target size. When target sizes of the right and left hands were different, and when the left hand was moving to the smaller of the pair of targets, there was a larger tendency for a first left-target fixation than when the left hand was moving to the larger of the pair of targets (Riek et al. 2003). They suggested that this could be the effect of an interaction between the visual system and the manual asymmetries of the right and left (dominant and non-dominant) hands.

This bias in gaze direction, predominantly towards the left hand target, seems to suggest an asymmetry in the utilization of feedback information (visual or proprioceptive) even in symmetric bimanual tasks in which the two hand movements are temporally synchronized. Flowers' feedback processing hypothesis (1975) suggests that differences between right and left hand performances are due to differences in the sensory or feedback control of movements, especially visual feedback. Roy and Elliott (1986) compared the speed-accuracy curves of left and right hands and observed that the left hand exhibited a steeper negative slope and hypothesized that this phenomenon was mainly due to the difference in the efficiency with which visual information was processed.

This behavior contradicts the claim of the left hand advantage (Goble and Brown 2008). If the left hand had an advantage for processing proprioceptive information (Goble et al. 2006; Goble and Brown 2007) and the right hand an advantage for processing visual information (Goble et al. 2008) then gaze orientation would be directed primarily to the right hand target, or be alternated infrequently to calibrate the left hand proprioception and thus allow more extensive use of proprioception to guide the left hand. The overwhelming predominance of gaze orientation to the left hand target, and more particularly right hand movements without direct visual feedback of the destination target rather indicate a necessity of visual guidance for the left hand. This behavior is in agreement with the asymmetry of position sense (Adamo and Martin 2009) associated to an asymmetry of the respective proprioceptive systems resulting from an asymmetry of cortical structures shown in humans (Kim et al. 1993; Classen et al. 1998; Baraldi et al. 1999) and animals (Nudo et al. 1992; Nudo et al. 1996). Based on this asymmetry, the sensorimotor resolution is presumed to be better for the right than left hand systems, which leads to a gain higher for the left than right hand proprioceptive sensory-motor loops (Adamo and Martin 2009), and is compatible with the necessity of greater visual control of the left hand and thus more extensive use of visual than proprioceptive feedback in the guidance of left hand movements. Hence, the recording of eye movements in our experiment point to an asymmetry in the quality and usage of feedback mechanisms underlying the respective control of each hand system.

2.4.3. Conclusion

Although the movements of the two hands are always temporally synchronized until peak velocities are achieved, this symmetry breaks down due to competing task demands of the two hands. This initial temporal synchrony, regardless of task conditions, seems to suggest that temporally synchronous hand movements could be the default mode of bimanual movements. This is supported by Meesen et al's hypothesis (2007) that coordination patterns associated with bimanual movements that are in-phase would be the preferred mode of movements since they would be performed with higher accuracy and stability. Furthermore, Oliveira et al. (2005) have suggested that the rigidity of temporal coupling during the initial phases of bimanual movements could be associated to their reliance on proprioceptive, rather than visual feedback. Vershchueren et al. (1999) have similarly hypothesized that this initial temporal synchrony of inter-limb movements could be attributed to a proprioceptive triggering mechanism, since the characteristics of inter-limb coupling appear to be controlled by proprioceptive information from both limbs. They hypothesized that the CNS might use a proprioceptive monitoring mechanism to maintain a stable phase relationship between the two arms.

The initial temporal synchrony breaks down during the terminal phases of movements, probably due to their increased reliance on visual feedback and the fact that the visual demands of the two tasks cannot be met simultaneously. This is evidenced by the emergence of different eye-hand coordination patterns as a function of task parameters during the terminal phases of movements. The point at which this temporal symmetry would break down as a function of task parameters is still an open question. Analysis of the spatial characteristics of eye-hand coordination patterns observed in this study might yield more information that might help answering this question. As visual acuity degrades with eccentricity from the line of sight, the relationship between gaze orientation and hand movements seems to reflect a trade-off between accuracy and synchronization.

Eye movement strategies observed in this experiment also indicate that irrespective of temporal coupling of the left and right hand movements (as observed in the movement kinematics), there seems to be an asymmetry in the feedback processing capacities of the left and right hemispheres. This is in accordance with earlier studies that have observed asymmetries in feedback processing capabilities of left and right hemispheres (Sainburg and Kalakanis 2000; Sainburg 2002; Sainburg and Schaefer 2004; Wang and Sainburg 2004). Depending on task difficulty, this asymmetry may or may not be reflected in differential temporal coupling of the hand movements. An understanding of the underlying mechanisms that cause the observed patterns of temporal coupling would also hold important implications to the question of whether this coupling of movements is preplanned, as in the temporal planning models (Jeannerod 1981, 1983, 1984; Hoff & Arbib 1993), or whether the coupling emerges without any pre-structured kinematic plan and just as a consequence of the system's attempt to manage the information processing demands of each task (Bootsma et al. 1992). Currently, the temporal variability in the onset of de-synchronization and dependence of gaze strategies on task characteristics seem to point in favor of the information processing hypothesis (Bootsma et al. 1992).

CHAPTER 3

EYE-HAND COORDINATION IN SYMMETRIC BIMANUAL TASKS: SPATIAL ASPECTS

3.1. Introduction

Temporal synchrony has been described as the most stable mode of coordination in rhythmic bimanual movements (Meesen et al. 2007). Discrete bimanual movements such as aiming and prehension show a tendency for the two limbs to interact to produce synchronous timing (Keele 1986; Kelso 1983; Jeannerod 1981). In bimanual prehension tasks, the two hands are temporally coupled during bimanual movements such that both hand movements are initiated simultaneously, they reach peak velocities and peak grip apertures at around the same time, and movement durations are also synchronized (Jackson et al. 1999, chapter 2). These authors suggested that the movement duration chosen in incongruent bimanual tasks is approximately the mean of movement durations of the two individual tasks. However, in the context of high-precision bimanual tasks, although temporal coupling during the initial acceleration phases of movements has been found to be tight and not easily over-ridden (Kelso et al. 1979, Martenuik et al. 1984, Fowler et al. 1991), this temporal synchrony seems to break down during the deceleration phases of movements, as the control of both hand movements require the simultaneous use of visual feedback, specific to each hand's task-goal (Balakrishnan et al. 2002, Bingham et al. 2008, Mason et al. 2008, chapter 2). Thus, both hands are, in essence, competing for the same resource. In this context, the extent of temporal synchrony during the terminal phases of movements was found to be dependent on individual task difficulties of the right and left hands, and the inter-target distance between them (discussed in the previous chapter).

This context-dependent temporal coupling of the two hands makes the question of spatial coupling in bimanual movements particularly interesting. Jackson et al. (1999) suggests that the problem of executing incongruent bimanual tasks (each hand is assigned a different task difficulty) is solved by synchronizing each limb movement to a common duration, and then scaling kinematic parameters like movement velocity and grip apertures of each hand independently. In a subsequent study on bimanual reversals to control cursor movements, Oliveira et al. (2005) suggest that online visual feedback specifically reduces the spatial coupling of movements. They suggest that the rigidity of temporal coupling during the initial phases of bimanual movements could be due to their reliance on proprioceptive, rather than visual feedback. In addition, coupled bimanual movements may be the default mode of movement, but the demand for visual feedback uncouples the movements spatially, possibly by independent corrections of the movement amplitudes of both hands. Recently, Mason et al. (2008) observed that spatial coupling of bimanual reach-to-grasp transport phases varied as a function of task parameters (object size and movement distance); however the spatial coupling of grasp phases remained weak, irrespective of task conditions. On similar lines, Dohle et al. (2000) suggested that different temporo-spatial coupling modes exist for the control of reach and grasp phases of bimanual prehension movements.

Thus, although there has been evidence of independent spatial control of each hand movement (Oliveira et al. 2005), there are still a number of unresolved questions: Is the spatial coupling/de-coupling intentionally programmed by the CNS? If so, what is the objective? Or like temporal synchrony, although intended to be synchronous, is the spatial asynchrony a consequence of the two systems trying to meet their respective feedback demands? What is the mode of spatio-temporal control in the context of high-precision bimanual tasks?

Our present study deals with bimanual “transfer-place tasks”, in which participants transferred two objects, one with each hand, and placed them onto their respective targets. Object sizes, target tolerances and the distance between targets of the two hands have been varied, while keeping the task demand symmetric (both task difficulties are the same, and movement distances are equal). The different eye-hand coordination patterns and their effects on temporal synchrony/asynchrony have been discussed in the previous chapter. In this chapter, the spatial coupling between the two hand movements in these trial conditions is discussed. Single-handed right and left hand movements were also recorded for the different object sizes and target tolerances, and bimanual movements are compared with their respective unimanual counterparts. The issue of left-right asymmetry and its effect on spatial coupling of bimanual movements is also studied.

3.2. Methods

Six right-handed individuals, four male and two female, aged 20-30 years, participated in this experiment as volunteers. All participants were naïve to the purpose of the experiment, with no prior experience at the specific tasks. They had normal vision and were free from neurological and musculo-skeletal disorders. The experiment was approved by the Institutional Review Board of the University of Michigan and all participants signed an informed consent form.

3.2.1. Experimental setup

The experimental task consisted of transferring objects, from specified initial positions to target locations. Unimanual transfers with the right & left hands, and bimanual transfers with a pair of objects, one in each hand were performed. For unimanual trials, object size and target tolerance were chosen as the task variables to be manipulated. Three pairs of light weight cylindrical objects, of height 120 mm, and diameters 8mm (obj 1), 18 mm (obj 2), 44 mm (obj 3) were used in the study. The weights of the objects were 8 gm, 22 gm and 60 gm respectively. The target diameter was defined with respect to the object diameter. For each object, the following three target tolerances were defined (fig 3.1):

1. Target diameter = object diameter + 0mm (tol1)
2. Target diameter = object diameter + 15mm (tol2)
3. Target diameter = object diameter + 45mm (tol3)

The object-to-target distance was set at 400mm for all trials.

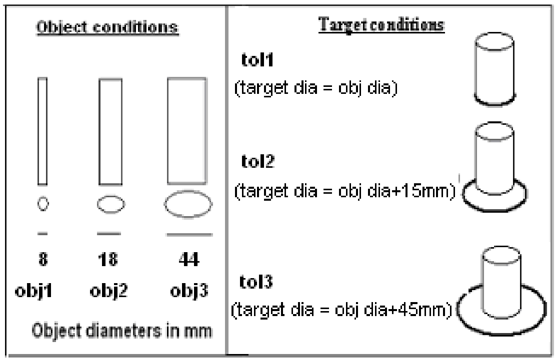


Fig. 3.1: Object and target conditions

In bimanual trials, apart from object size and target tolerance, the inter-target distance i.e., the distance of separation between the pair of targets was also varied. Distance between the pair of targets, defined as the distance between the two closest points on the target circles, was either 30 or 200mm, as shown in fig 3.2.

The initial object and final target locations were displayed as images on a 52” flat-screen TV placed horizontally at each subject’s elbow height (Fig 3.2). Subjects were seated in front of the TV such that the screen centerline was aligned with their mid-sagittal plane. The near edge of the screen was placed 250mm away from the participant’s pelvis. The screen‘s aspect ratio of 16/9 translated to a frame resolution of 1920 X 1080. At the initial locations, the centers of objects were 25mm away from the near-edge of the screen and ~ (380 + 0.5*inter-target distance + 0.5*target tolerance)mm from the mid-sagittal plane, while the target centers were positioned along a horizontal line that was 127mm away from the line joining the initial object centers. The centerline of the screen was used as the axis of symmetry to place the objects and targets. All trials were designed such that any hand’s transfer task consisted of moving objects from initial to final locations, both of which were always located on the same side of the subject’s mid-sagittal plane as that of the corresponding hand.

An image file, based on specifications for the object and target sizes and their respective locations, was created for each task condition. The sequence of image files was randomized and presented using a software interface to simulate each trial during the experiment.

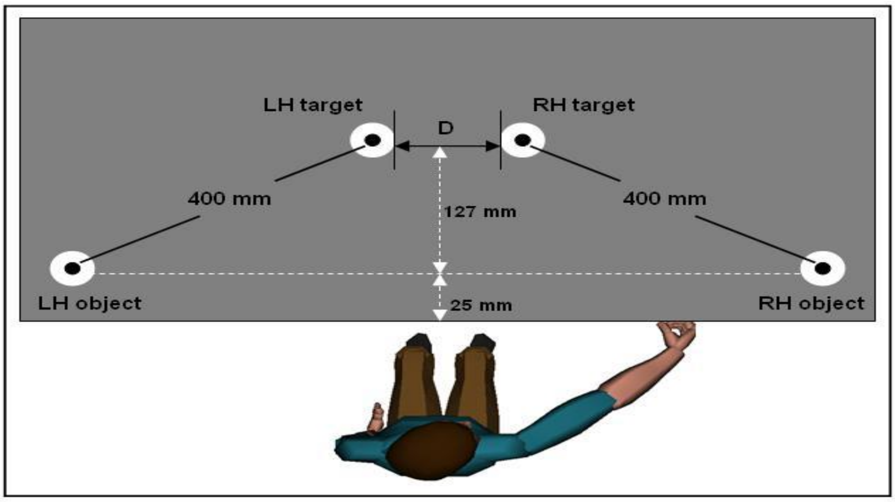


Fig. 3.2: Experimental setup showing the object and target locations on LCD screen (Note: D indicates distance between targets)

3.2.2. Movement recording

An eight-camera Qualisys® motion capture system was used to record kinematic data sampled at 60 Hz. Passive, reflective markers were placed on selected body landmarks to record the subject's hands, arms, torso and head movements as illustrated in Fig 3.3. Markers were placed on important body landmarks: head (3), left and right shoulders (2), elbows (2), wrists (2), sternum (3) and pelvis (2). Eye movements were recorded simultaneously using a head mounted eye tracking system (ASL eye trac 6.0®). The direction and point of gaze were also monitored on line on a video screen (fig 3.3). Both gaze and body movement signals were synchronized and recorded at 60 Hz. Video images of all trials were recorded using a JVCGR-DX97 video camera that was synchronized with the motion capture and eye-movement data collection.

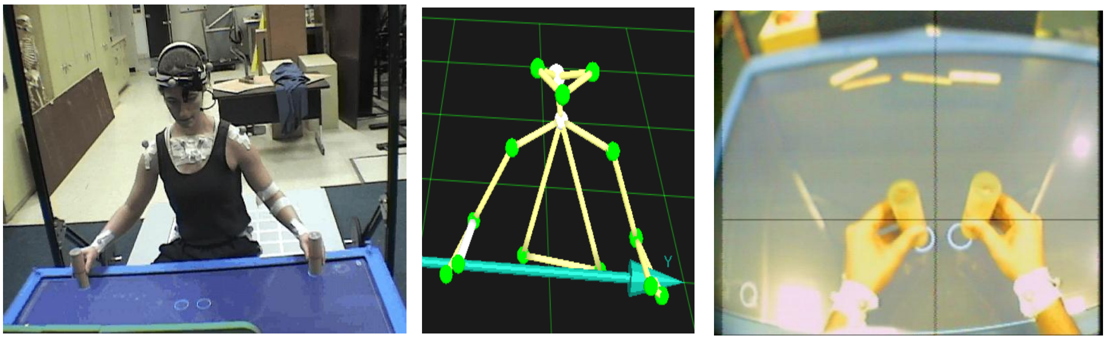


Fig. 3.3: (a) Motion capture and eye-tracker systems setup **(b)** Body linkage system **(c)** Example of a scene from the video camera mounted on the eye tracker: cross hairs indicate the point of gaze

Gaze data was obtained using a two-step calibration procedure. The first step was to calibrate the eye-in-head position using the standard 9 point calibration procedure provided by ASL. During this procedure, the head position was fixed using a bite-bar attached to a fixed frame. The calibration targets were presented on the actual work plane on the LCD screen surface. The next step was to calibrate the eye-in-space (gaze) orientation. The subject was asked to fixate five points sequentially while the head was free to move. The eye tracker measured the subject's eye-in-head signal for each target, while head position was simultaneously recorded using the motion capture system, to obtain the head-in-space signal. The spatial coordinates of each target were computed using the motion capture system. These datasets were combined to develop an offline calibration procedure to obtain gaze orientation (eye-in-space signal). Thus, to analyze gaze-hand coordination in a common frame of reference, the data pertaining to the line of sight was projected to the work plane defined in the real world coordinates of the motion capture system.

3.2.3. Procedure

In unimanual trials, subjects were instructed to move objects on to specified target locations with either their right or left hands, depending on the trial type. In bimanual trials, subjects were instructed to move a pair of objects, one with their left and the other with their right hands, from their respective initial positions to specified target locations. The left hand always picked the object on the left and moved it to the left target location, and vice versa for the right, i.e., the task did not require any crossing over of the two hands. No explicit instruction was provided to the subject about the expected sequence of movements and no constraints were imposed on speed of movements either.

The subjects started each trial with the objects already grasped in their hands, and the eyes fixating a target placed in the mid-sagittal plane at eye level. This initial eye-position was standardized so that the quality of visual information about the targets was the same for all subjects at the start of each trial. This point was fixed in the mid-sagittal plane so that the subject's choice of the first point of fixation during the trial could be observed clearly. On receiving the cue to start, the objects were transferred to the target locations, and held there until the end of the trial without changing hand positions, but gaze was returned to the initial target fixation, after the end of hand movements. Despite the subjects holding the objects at the target position until the end of the trial, kinematic parameters were defined to identify the end of hand movements in each trial. However, for the gaze data, returning the gaze to the initial-home position made the identification of the end of gaze movements in each trial very easy to define. A pinch grasp was used to hold all objects. Thumbprints were placed on all objects to standardize the grip locations. Movement speed was not specifically constrained, and subjects were asked to move at a comfortable pace to complete the task. The only constraint imposed on task-performance was zero error tolerance in the accuracy of positioning.

Since the pilot studies indicated the development of consistent eye-hand coordination strategies with learning, experimental data collection was initiated after 100 practice/learning trials. The set of 100 practice trials were picked randomly from the actual experiment trials and the subjects were not aware that these practice trials were excluded from the analysis. Each condition was repeated thrice during the experiment trials. All conditions were randomized and inter-trial intervals were of approximately 15 seconds. Before each trial, the subject was allowed to see the locations of the objects and the targets. If the accuracy constraints were not met in any of the trials, those corresponding trials were repeated at the end of the experiment.

For trials in which the target size was larger than the object size, the objects had to only be placed within the limits of the target area and did not have to be centered. The objects had to be moved and brought in vertically. The participants were not allowed maneuvers such as pivoting one end of the object at an angle and rolling it in to the target zone, or sliding the objects on the surface of the screen. Adjustments or corrections were not allowed after the object made contact with the surface. In addition, subjects were also instructed to refrain from bracing/supporting their arms on any surface.

3.2.4. Experimental design

In unimanual trials, Object size (8, 18 and 44mm), and target tolerance (0, 15, 45mm) were the independent variables, thus yielding a 3^2 factorial design for each hand. Three replicates were used for each condition. Thus a total of 27 trials (9 conditions X 3 repetitions) were recorded for each hand, yielding 54 unimanual trials in all. The labeling convention used to identify the trial type was: “Hand – object size – target tolerance”. For instance, “R 8-0” would mean a unimanual trial performed with the right hand, with 8mm object diameter and 0 mm target tolerance.

In bimanual trials, object size (8, 18 and 44mm), target tolerance (0,15 and 45 mm) and the distance between targets (30 and 200 mm) were the independent variables, which yielded a 3X3X2 mixed level factorial design. Three replicates were used for each condition. Although all three parameters were varied, they were set at the same level for each hand within a trial, to ensure symmetric task constraints between the two hands. Thus a total of 54 trials (18 conditions X 3 repetitions) were recorded for each participant. The labeling convention adopted to identify the trial type was:
“LH object – LH target tolerance – distance between targets – RH target tolerance – RH object”

According to this convention, a trial of type “8-15-200-15-8” means that LH and RH object sizes are 8mm, target tolerances are 15mm (i.e. the target diameters are 23mm), and the distance between the two targets is 200mm.

3.2.5. Data analysis

The three dimensional data from the motion capture system was filtered using a second order, low pass Butterworth filter with a cut-off frequency of 6 Hz. The kinematic data from the markers placed on the wrists were used to calculate the onset and end times of movements. Movement onset corresponded to the first instant at which the magnitude of tangential velocity of the wrist marker exceeded 5 mm/sec. The end of movements was defined as the first instant after the occurrence of peak velocity, at which the object came in contact with the LCD screen surface (observed from synchronized video recordings of the trials), and the magnitude of tangential velocity of the wrist marker fell below 5mm/sec. This dual constraint was used to define the end of movements, because it was observed that in some trials, when the primary hand entered its final task-completion phase, the secondary hand would hover at an intermediate point in its trajectory. So although the magnitude of wrist velocity of the secondary hand fell below 5mm/sec at an intermediate point of its trajectory in such cases, the hand would then continue to move after that, in order to reach the target position. Ensuring that the hand has reached its target position and the magnitude of the wrist tangential velocity has fallen below the defined threshold helped in eliminating any confusion about the end of movement.

The raw eye-position data was converted to a series of fixation events by EyeNal, the offline data analysis program provided by Applied Systems Laboratory (ASL) for processing eye movement information. The EyeNal program used a moving window technique with the following parameters to calculate fixations: A fixation was started when the standard deviation of 6 consecutive samples of raw eye-position data (corresponding to about 100 ms) fell within 0.5 degrees of visual angle and was ended when 3 consecutive samples fell outside of 1 degree. The fixation duration was calculated as the amount of time between the first data sample of the starting samples and the sample immediately preceding the first of the ending samples. The fixation position was calculated as the mean position of all samples that fell within a visual angle of 1.5 degrees. Blinks (pupil losses up to a maximum of 200ms) were ignored and did not terminate fixations.

The resolution of the eye tracker was less than a degree. However, since the work plane was not always normal to the head-mounted eye tracker, the actual resolution obtained was less than that indicated in the specifications. The resolution was assumed to be of the order of ~1 degree since the calibration plane was almost a meter away from the subject’s eye, and this translated to a spatial error of ~ 17 mm. As the target sizes were of the same order of magnitude, gaze orientation was only used to define landmark zones corresponding to one target or the other, and not to identify the exact point of foveation at any given point of time. Landmark zones were defined as concentric circles of diametric tolerance of 10mm about the respective targets. The coordination of gaze and hand actions was described in terms of the temporal coordination between gaze shifts entering and exiting landmark zones (each hand’s target) and the specific kinematic events associated with the hand movements. The maximum distance between the targets in the experiment was only 200mm, (corresponding to an approximate visual angle of ~12 degrees). Since the data was sampled at 60 Hz, the gaze shift from one target to the other appeared almost instantaneous. The shift was often complete within 1-2 frames of measurement.

Hence, in this study, gaze shifts have been assumed to be instantaneous. The foveal field of view was defined to subtend a solid an angle of ~2 degrees about the line of gaze and the peripheral field of view, up to 20 degrees (Jeanerrod and Prablanc, 1983).

In bimanual trials, the hand that moves to the target which is fixated first during the experiment is defined as the "primary" hand, and the other hand is referred to as the "secondary" hand in this study. It was observed in a previous study (Srinivasan et al. 2009) that in bimanual trials in which both left and right hand placements on to their respective targets occurred simultaneously, the left hand was the primary hand in 89.33% of all trials. In bimanual trials in which placements occurred sequentially, the left hand was the primary hand in 91.18% of trials, and the order of placements was such that the primary hand completed its placement first, followed by the secondary hand. Thus, since in ~90% of all bimanual trials, the left hand was the primary hand and the right hand was the secondary hand, all subsequent analyses on bimanual movements in this study are performed only on those bimanual trials in which the left hand was the primary hand.

From the time of movement onset, the time taken by each hand to attain its peak velocity (Tpv) was computed in unimanual and bimanual trials as the time instant when the magnitude of the wrist tangential velocity profile (speed) reached its peak. Repeated measures ANOVA was performed for unimanual trials: with hand (Right/Left), object size and target tolerance as between-subjects factors, and Tpv as the dependent measure. Correspondingly, for the repeated measures ANOVA analysis of bimanual trials, hand (Primary/Secondary), object size, target tolerance and inter-target distance were chosen as the between-subjects factors and Tpv was the dependent measure. The distances traveled by each hand from the movement onset up to the time of peak velocity (Dpv) were computed by integrating the speed, from movement onset up to Tpv. This was expressed as a percentage of the total distance of movement, from the object's initial to final position in the trial (computed by integrating speed profiles over the total time of movement). Thus Dpv of any hand in a movement = (Distance traveled up to instant of peak velocity / Total distance of movement) * 100.

In unimanual trials, repeated measures ANOVA analysis was performed with hand (Right/Left), object size and target tolerance as the between-subjects factors, and Dpv as the dependent measure. In bimanual trials, a repeated measures ANOVA was used to analyze the effects of task parameters (object size, target tolerance and the inter-target distance) on the Dpv values of the primary hand. Since the left hand was the primary hand in the bimanual trials, the performance of the left hand under unimanual and bimanual conditions was compared by comparing the primary hand movements in bimanual conditions with the left hand movements in unimanual conditions. Further, in bimanual trials, the ratio of Dpv of the secondary (right) hand to that of the primary (left) hand was defined as ‘distance fraction ratio’ (DFR) and a repeated measures ANOVA was run to analyze the effects of object size, target tolerance and inter-target distance on DFR.

3.3. Results

3.3.1. Time-to-peak velocity

In all unimanual trials, peak velocities occurred at about the same time, irrespective of which hand was used for making the movement (right/left) and the task precision. Repeated measures ANOVA analysis indicated that the main and interaction effects of hand, object size and target tolerance did not significantly influence Tpv (table 3.1). Similarly, the primary and the secondary hands reached the peak velocities at about the same time. Typical speed profiles of the primary and secondary hands in bimanual trials corresponding to a subject are illustrated in fig 3.4. Neither the hand (primary/secondary), nor did any of the task parameters have a significant effect on Tpv in bimanual trials (table 3.2). Hence, average Tpv values of both hands were collapsed across unimanual trials and bimanual trials respectively. No significant difference was observed between the means of the unimanual and bimanual trial Tpvs ($P > 0.5$). Thus, both left and right hands reached their peak velocities at about the same time, irrespective of whether one hand moves alone, or both hands move together, and irrespective of the task precision, as long as the distance of movement was the same.

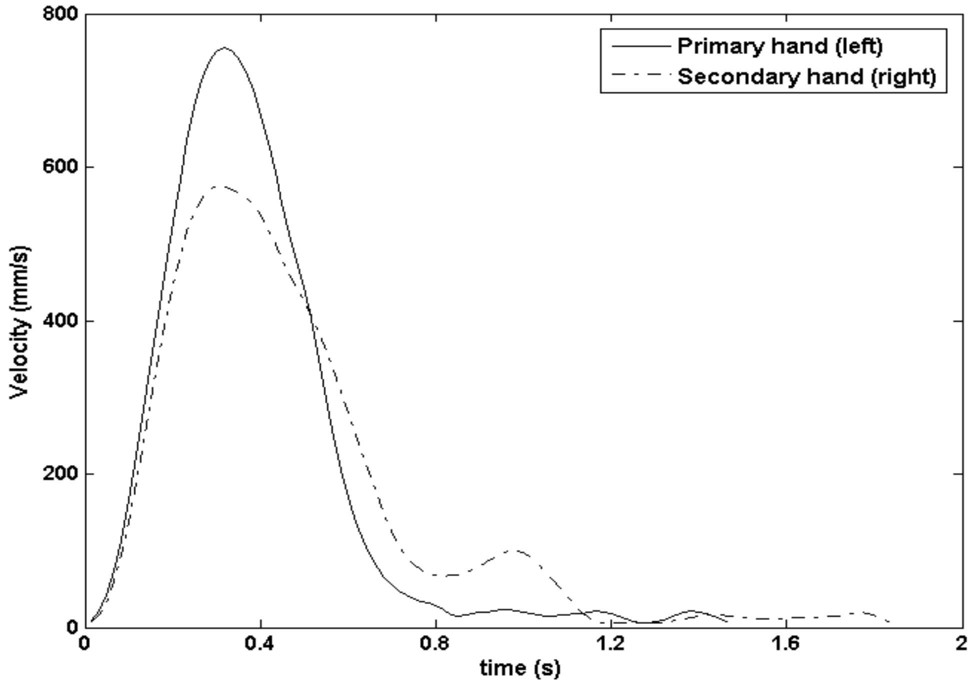


Fig. 3.4: Typical velocity profiles of right and left hands in a bimanual trial of type 44-0-30-0-8 of subject 2

Table 3.1: Repeated Measures ANOVA: effect of hand & task conditions on Tpv and Dpv in unimanual trials

General Linear Models **(alpha = 0.05)**		**Tpv**		**%Dpv**	
Factor	**DOF**	**F stat**	**P-value**	**F stat**	**P-value**
Hand	1	0.030	0.863	5408.1	<.001
Object size	2	0.450	0.639	1.401	0.252
Target tolerance	2	1.155	0.320	0.141	0.869
Object size*Target tolerance	4	0.201	0.937	0.636	0.638
Hand*Object size	2	0.181	0.835	1.463	0.237
Hand*Target tolerance	2	0.058	0.944	0.751	0.475
Hand*Object size*Target tolerance	4	1.074	0.374	0.821	0.515
Error	90				

Table 3.2: Repeated Measures ANOVA:effect of hand & task conditions on Tpv in bimanual trials

Factor	DOF	F stat	P-value
Hand	1	0.036	0.850
Object size	2	1.269	0.284
Target tolerance	2	0.056	0.945
Inter-target distance	1	0.063	0.801
Hand*Object size	2	0.110	0.896
Hand*Target tolerance	2	0.859	0.425
Hand*Inter-target distance	1	0.063	0.801
Object size*Target tolerance	4	0.354	0.841
Object size*Inter-target distance	2	1.083	0.341
Target tolerance*Inter-target distance	2	0.215	0.807
Hand*Object size*Target tolerance	4	0.586	0.673
Hand*Object size*Inter-target distance	2	1.041	0.355
Hand*Target tolerance*Inter-target distance	2	0.280	0.756
Object size*Target tolerance*Inter-target distance	4	0.619	0.649
Hand*Object size*Target tolerance*Inter-target distance	4	0.304	0.875
Error	180		

3.3.2. Distance traveled up to instant of peak velocity

Fig 3.5 shows the Dpv of right and left hand movements in unimanual trials as a function of different task precision for the different subjects.

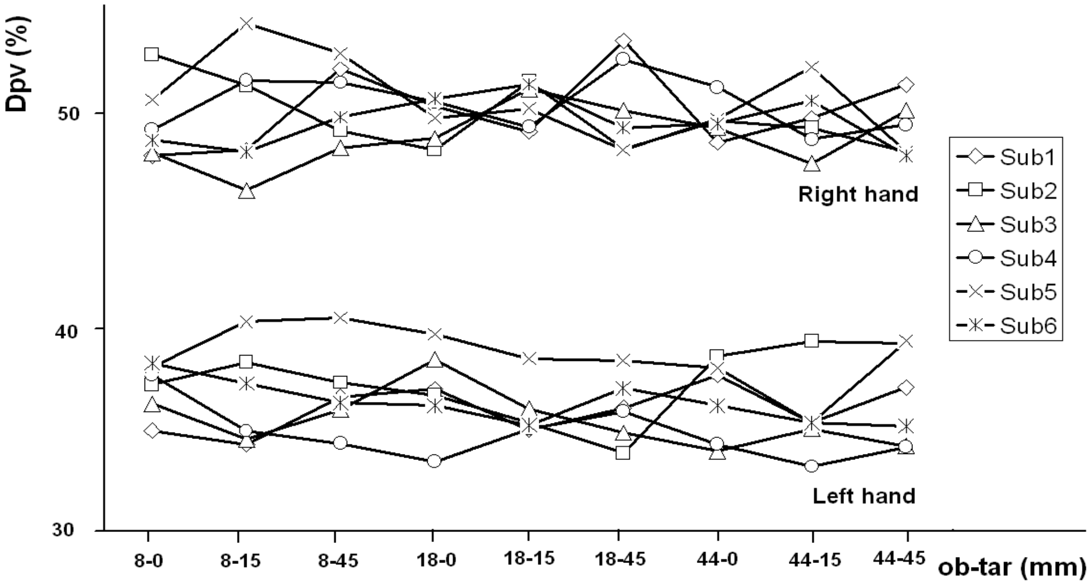


Fig. 3.5: %Distance to peak velocities (Dpv) of right & left hands as a function of task precision

Repeated measures ANOVA analyses on Dpv indicated that in unimanual condition, neither hand's Dpv was significantly influenced by task precision (object size, target tolerance) (***P*** = 0.252, 0.869 respectively). Thus the distance moved by the right hand up to the instant of peak velocity, remained the same, irrespective of task precision when the total distance to target was the same in all unimanual trials. A similar trend was also observed for movements made by the left hand. However, the hand (Right/Left) effect was significant on Dpv (***P*** < 0.001). None of the interactions were significant (refer to table 1 for the ANOVA results). Fig 3.6 illustrates the difference in Dpv between the right and left hands in unimanual trials.

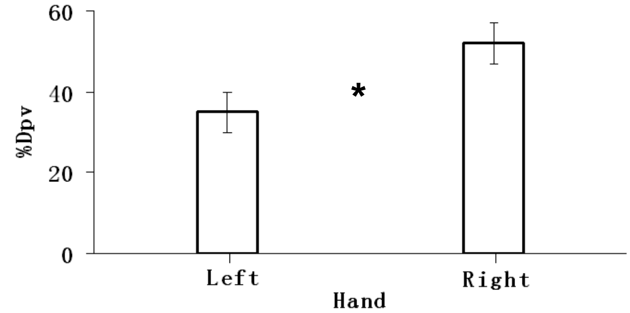


Fig. 3.6: Main effect of hand on Dpv in unimanual trials

Fig 3.7 illustrates the average Dpv of the right-handed movements, collapsed across all task conditions, compared to the average Dpv of the left-handed movements for all subjects. It was observed that on average, the right hand tended to move a greater distance to target during the acceleration phases of unimanual movements, when compared to the left hand, when both hands were moving over the same total distance to target. This trend was observed consistently across all subjects.

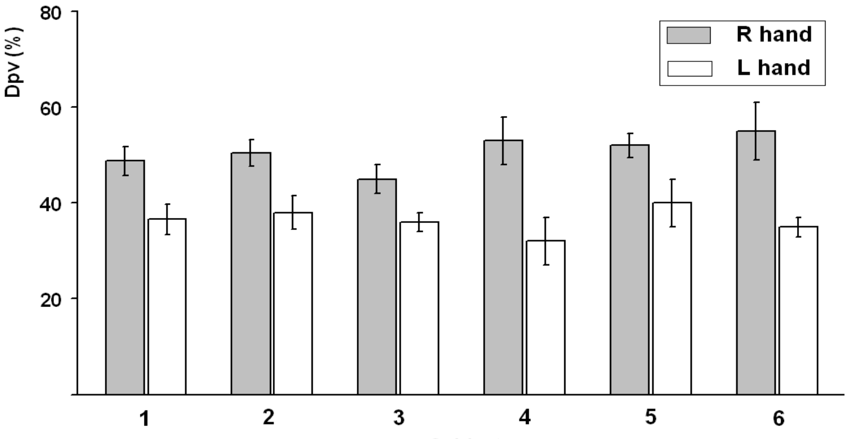


Fig. 3.7: Average Dpv of right and left hands in unimanual trials

Fig 3.8 shows the typical Dpv of the primary and secondary hands of one subject during bimanual conditions. A repeated-measures ANOVA performed on the primary hand's Dpv indicated that the object size, target tolerance and inter-target distances did not affect Dpv of the primary hand significantly in bimanual conditions (***P*** > 0.5; table 3.3).

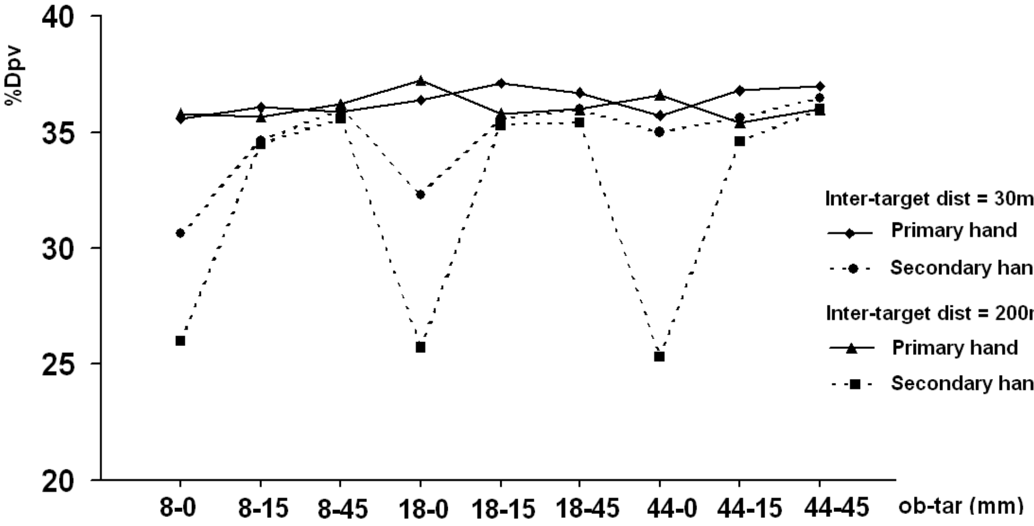


Fig. 3.8: Typical percentage distances moved by primary and secondary hands up to peak velocity during different bimanual conditions for 1 subject

A comparison of the average primary hand %Dpv in bimanual trials, collapsed across task parameters, and the average left-hand %Dpv in unimanual trials, is illustrated in fig 3.9. The mean %Dpv values of the primary hand in bimanual conditions and the left hand in unimanual conditions were not significantly different (***P*** = 0.37).

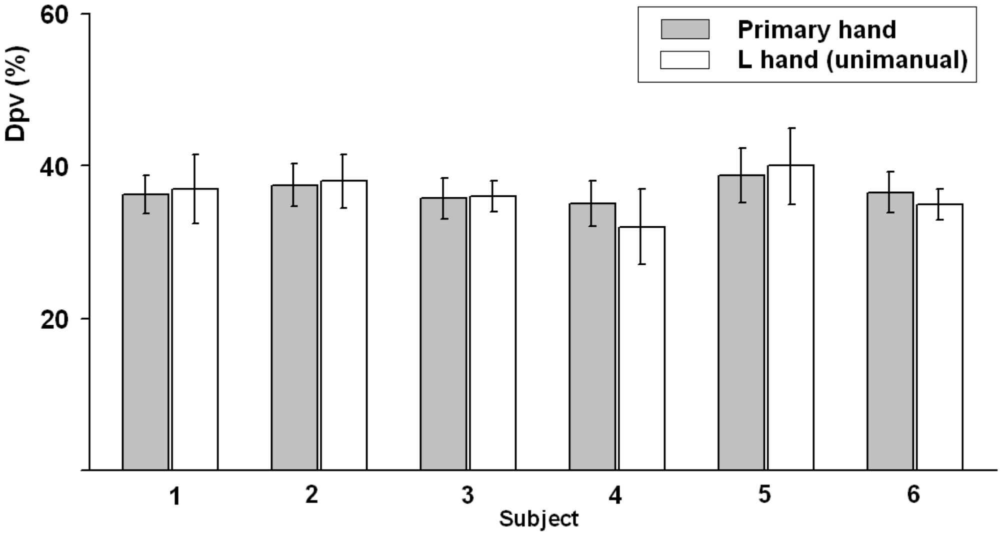


Fig. 3.9: Average Dpvs of left hand in unimanual and bimanual trials

3.3.3. Distance- fraction ratio (DFR)

The right hand covers more distance to target than the left at the time of peak velocity in unimanual trials. However, in bimanual trials, when the left hand is the primary hand, the right hand being the secondary hand travels lesser distance to target than the left hand, when observed at the time of peak velocity. The ANOVA performed on the distance fraction ratio (DFR) between the secondary and primary hands indicated that both the main and interaction effects of object size, target tolerance and inter-target distance were significant (table 3.3). DFR increased with increasing object size and target tolerance, and decreased with increasing inter-target distances (fig 3.10).

Tukey's pair-wise comparisons indicated that varying the object size from 8 to 18 mm did not have a significant effect on DFR (***P***=0.13). However, the difference in DFR was significant when object size was changed from 18 to 44 mm (***P***=0.006). Similarly, varying the target tolerance from 0 to 15 mm had a significant effect on DFR| (***P***=0.24). However, varying the target tolerance from 15 to 45 mm did not affect DFR significantly (***P***=0.002).

Table 3.3: Repeated measures ANOVA - effect of task conditions on Dpv of primary hand and DFR

General Linear Models (alpha = 0.05)		**Dpv**		**DFR**	
Factor	**DOF**	**F stat**	**P-value**	**F stat**	**P-value**
Object size	2	0.381	0.685	6.8	0.002
Target tolerance	2	1.010	0.368	555.4	<0.001
Inter-target distance	1	0.009	0.925	9.1	0.003
Object size*Target tolerance	4	0.449	0.773	11.3	<0.001
Object size*Inter-target distance	2	0.244	0.784	8.4	0.001
Target tolerance*Inter-target distance	2	0.028	0.973	46.4	<0.001
Object size*Target tolerance* Inter-target distance	4	0.083	0.988	8.1	<0.001
Error	90				

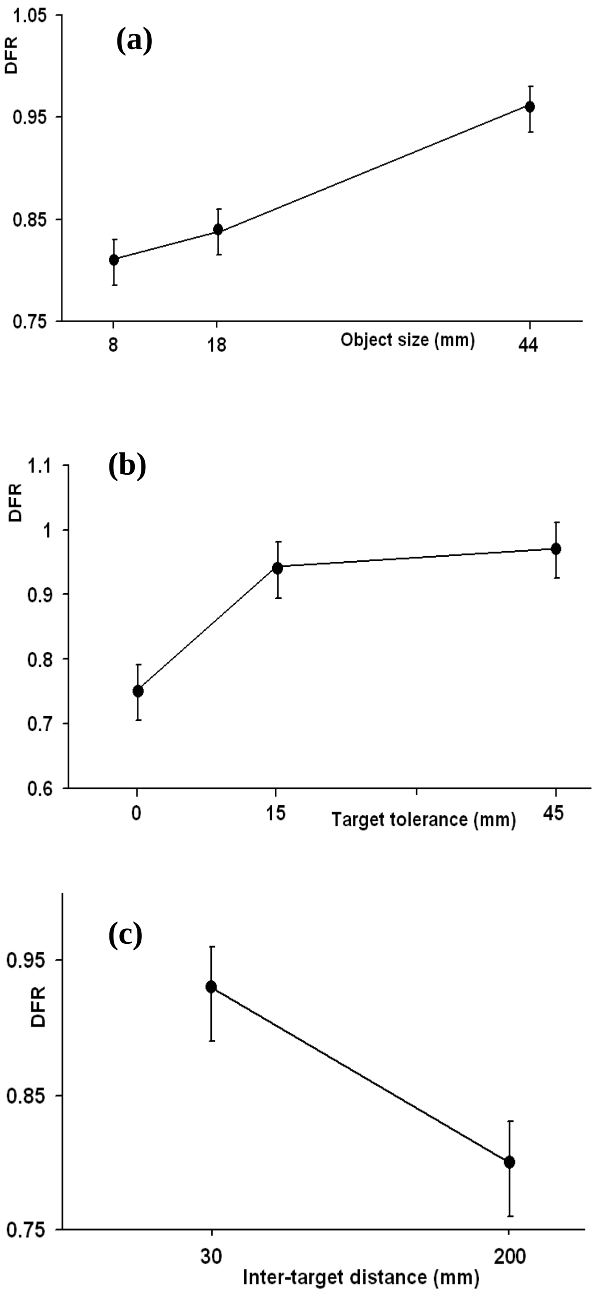


Fig. 3.10: Main effects of: (a) object size, (b) target tolerance and (c) inter-target distance on DFR

Interactions of object size, target size and distance between targets were also found to be significant ($\boldsymbol{P} > 0.001$; table 3.3), as illustrated in fig 3.11.

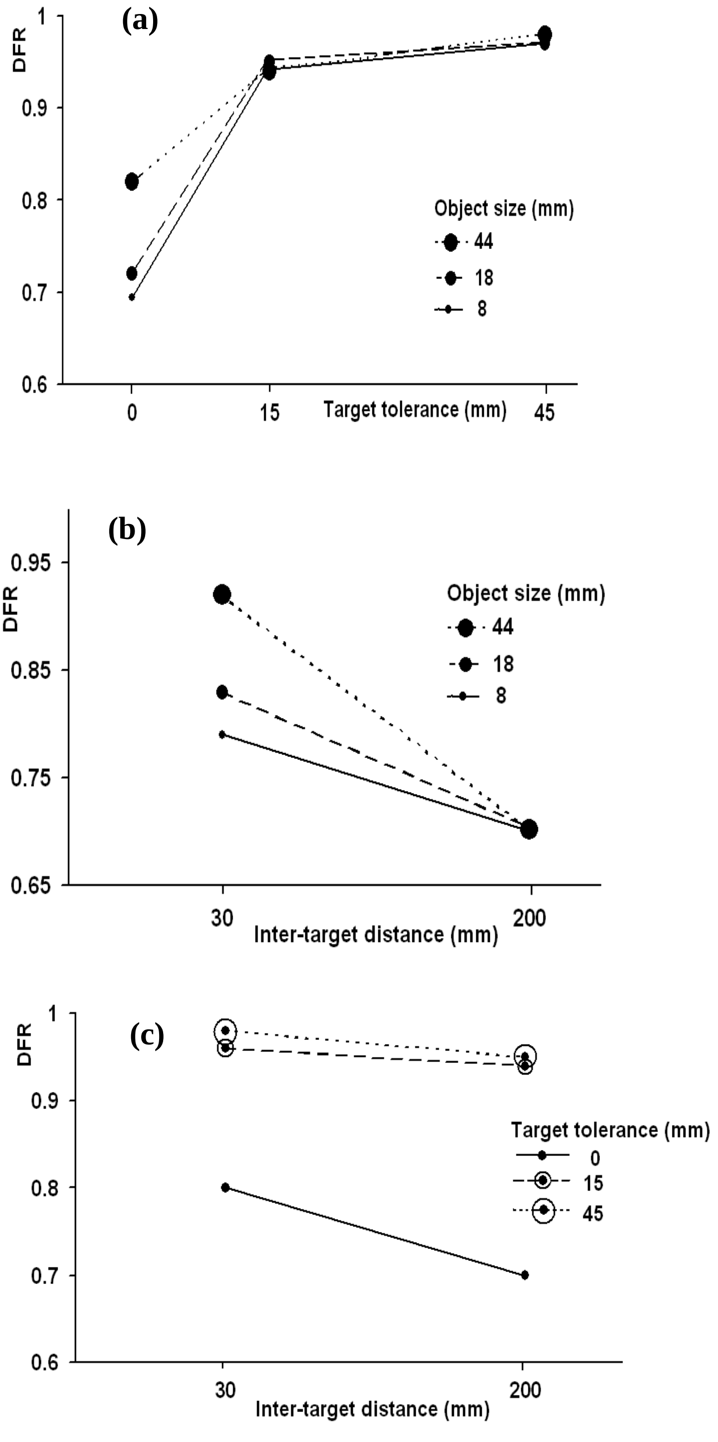


Fig. 3.11: : Interaction plots with fitted means of DFR: **(a)** Object size*Target tolerance; **(b)** Object size*Inter-target distance; **(c)** Target tolerance*Inter-target distance

Tukey’s pair-wise comparisons of the interaction effects of object size vs. target tolerance shows that although DFR increases with increase in object size for the smallest target tolerance (0mm), it did not change significantly with object size at higher target tolerances. Similarly, the interaction effects of object size vs. distance between targets in Fig. 3.11 indicate that the decrease in DFR with increase in distance between targets was significant for all object sizes.

The interaction effects of target tolerance vs. distance between targets (Fig 3.11) indicate that the decrease in DFR with increase in distance between targets was highest when the target tolerance was smallest (0 mm). DFR did not vary significantly by changing the distance between targets for higher target tolerances of 15 and 45 mm. Table 3.4 presents the results of Tukey's tests for the two-way interactions of the highest and smallest values of the three factors: object size (ob), target tolerance (tar) and distance between targets (dist).

Table 3.4: Tukey's pair-wise comparisons of specific interaction effects

Level 1	**Level 2**	**P value**
Ob 8mm, Tar 0mm	Ob 44mm, Tar 0mm	0.0004
Ob 8mm, Tar 45mm	Ob 44mm, Tar 45mm	0.8125
Dist 30mm, Ob 8mm	Dist 200mm, Ob 8mm	0.0005
Dist 30mm, Ob 44mm	Dist 200mm, Ob 44mm	0.0003
Dist 30mm, Tar 0mm	Dist 200mm, Tar 0mm	<0.0001
Dist 30mm, Tar 45mm	Dist 200mm, Tar 45mm	0.7401

3.3.4. Variation of DFR across different eye-hand coordination strategies

Table 3.5 shows the classification of eye-hand coordination strategies according to task parameters (described in Srinivasan et al. 2009), and also the mean values of DFR, grouped according to eye-hand coordination strategies. In selective, predictive and intermittent gaze strategies, the mean DFR values were ~1, indicating that the secondary hand traveled almost the same distance as the primary hand, up to the instant of peak wrist velocity. Since post-hoc analysis indicated that inter-target distance significantly affected Dpv at zero-target tolerance, the terminal gaze behavior (observed at both inter-target distances of 30 and 200 mm) was split into two different blocks, based on inter-target distance. DFR observed in the trials in which subjects adopted terminal gaze strategies were significantly smaller than the means of DFR observed in other strategies. That is, the distance traveled by the secondary hand up to peak velocity was reduced when a terminal gaze strategy was used.

Table 3.5: Mean Distance Fraction Ratios, classified according to eye-hand coordination strategy

Object size	Target tolerance	Inter-target distance	Gaze strategy	Mean DFR
low	low	low	terminal	0.824 ± 0.035
low	low	high	terminal	
high	low	high	terminal	0.730 ± 0.039
high	low	low	intermittent	0.958 ± 0.036
low	high	low	selective	0.987 ± 0.011
high	high	low	selective	
low	high	high	predictive	0.965 ± 0.024
high	high	high	predictive	

Fig 3.12 shows the mean Dpv of the primary hand, and the secondary hand during different gaze behaviors for each subject. From this figure, it is evident that the trends observed in mean DFRs classified according to gaze strategies in table 3.5, are consistent across all subjects.

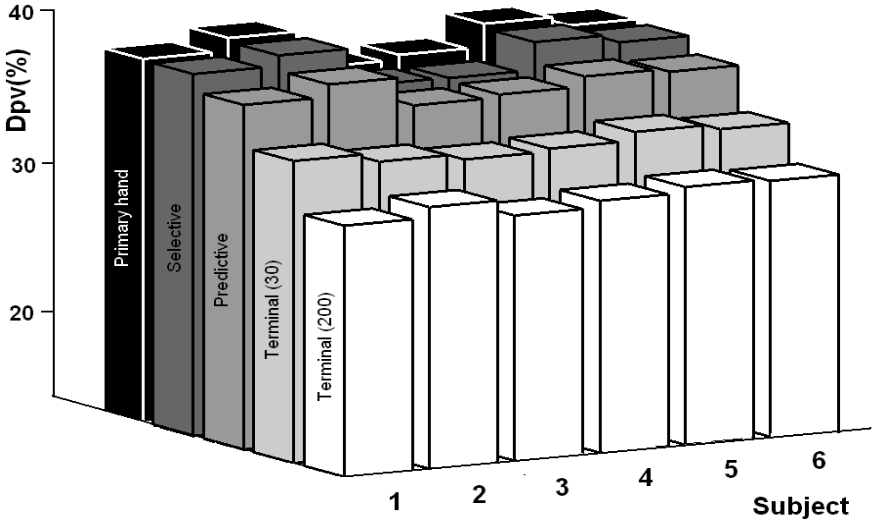


Fig. 3.12: Dpv of primary and secondary hands in different gaze strategies

3.3.5. Distance traveled up to gaze shift

In bimanual trials in which the predictive strategy was adopted, the distances traveled by both primary and secondary hands up to the instant of a target gaze-shift were computed, and Dgs was defined as:

$$\text{Dgs} = \frac{(\text{Total distance to target} - \text{Distance up to instant of gaze shift})}{\text{Total distance to target}} * 100$$

Although each subject traveled different distances with their primary and secondary hands up to the instant of gaze shift, both primary and secondary hands seem to have traveled similar distances to their respective targets at the time of gaze shift within each subject (fig 3.13).

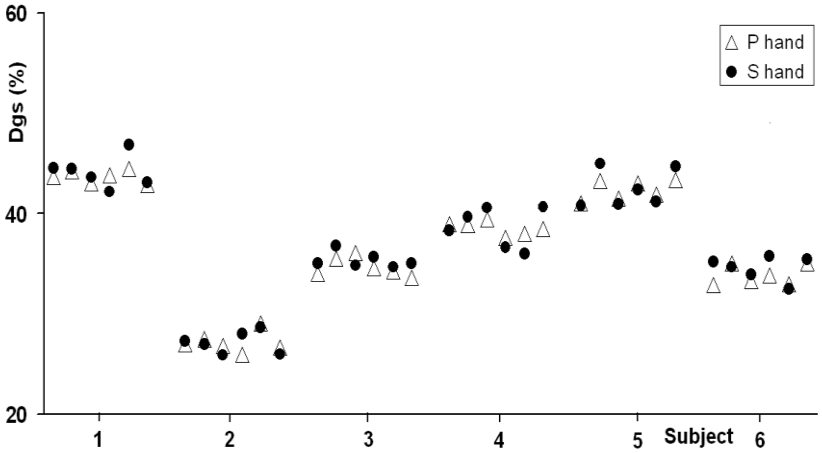


Fig. 3.13: Dgs of the primary and secondary hands during the predictive gaze strategy

The Dgs of the secondary hand during trials in which the terminal gaze strategy was used are presented in fig 3.14. Since the gaze transition from primary to secondary target occurs after the primary hand reaches its target in this strategy, the Dgs of the primary hand is always zero and is hence not presented. In the trials in which subjects adopt the terminal strategy of movement, Dgs of the secondary hand is higher for the 200 mm than the 30 mm inter-target distance. Thus, the secondary hand has traveled more distance to target by the time gaze shift occurs in cases when inter-target distance is small, when compared to those trials in which inter-target distance is higher. This difference in the distance traveled by the secondary hand with inter-target distance in terminal gaze strategy trials is statistically significant (***P***<0.001).

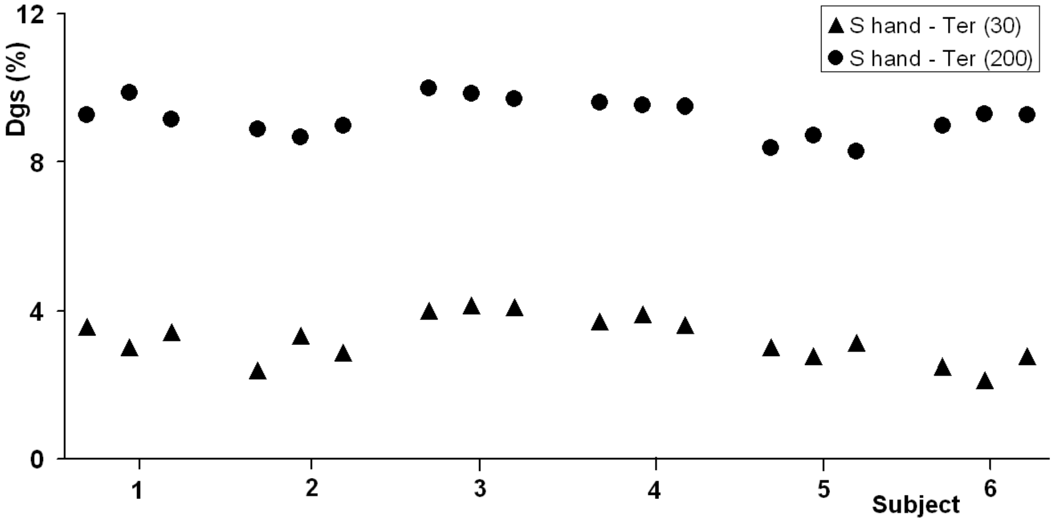


Fig. 3.14: Dgs of the secondary hand during the terminal gaze strategy

3.3.6. Correlation between Dpv and Dgs of the secondary hand during terminal gaze strategy

The high correlation co-efficient (-0.86), between Dpv and the Dgs of the secondary hand during the terminal strategy trials indicates that when the secondary hand travels a greater distance up to peak velocity, it has subsequently also traveled a greater distance up to its gaze shift.

3.4. Discussion

3.4.1. Unimanual conditions

For a fixed distance to target, each hand reached peak velocity at almost the same time across all trials, irrespective of task conditions (object size and target tolerance). Similarly, within each hand, Dpv was similar across all task difficulties. This is in accordance with earlier observations that the time-to-peak velocity and the magnitude of the peak velocity depend mainly on the amplitude or distance of movement, and are independent of task difficulty. Since feedback information about the target is processed and used to make corrections in movements only during the deceleration phases of movements, the length of deceleration phases has been observed to be dependent on task difficulty, while both the time of acceleration phases and the distance traveled during the acceleration phases are independent of task difficulty (Roy 1983).

However, when compared between the right and left hands, although the time to peak velocity remained similar between the two hand movements, the distance moved by each hand in the time from movement onset to peak velocity varied, depending on which hand was used for the task. In other words, the peak velocity attained by the right hand was significantly greater than that of left hand in unimanual tasks, even while moving to the same target. Similar observations of common acceleration times, with right hands attaining higher peak velocities than left hands, have been made by Roy et al. in their studies on manual asymmetries. These observations led them to hypothesize that the right hand has an advantage for processing visual feedback information over the left hand. From this hypothesis, they also predicted that the hands would differ not in the time-to-peak velocity, but in the time-after-peak velocity, the kinematic variable most sensitive to feedback processing with the right hand spending lesser time than the left (Roy 1983; Roy and Elliot 1986, 1989; Roy et al. 1994).

Thus our results in the unimanual section were all in accordance with previous studies investigating the hand kinematics of right-handed individuals, in the performance of right and left handed ipsilateral aiming and reach movements.

3.4.2. Bimanual Conditions

In symmetric bimanual conditions, both right and left hands reached their respective peak velocities at the same time, irrespective of task difficulty. Furthermore, the time-to-peak velocities of the right and left hands were also similar irrespective of whether the task was unimanual or bimanual. This suggests that during the execution of concurrent motor responses, there seems to be no additional cost associated with performing two tasks simultaneously, during the initial acceleration phases of movements.

Since the left hand was the primary hand in ~90% of bimanual trials, any subsequent references to “primary hand” implies a reference to the left hand, and the secondary hand is the right hand. In the unimanual conditions, the right hand’s Dpv is significantly greater than the left hand’s Dpv, irrespective of task conditions. However, in the bimanual trials, while the primary (left) hand has a Dpv similar to that of the left hand under unimanual conditions, the secondary (right) hand has a Dpv either similar to or significantly less than that of the primary hand. Thus, the left hand seems to be the predominant choice as the primary hand, and the distance moved by the primary hand during the acceleration phase of a bimanual movement seems to be relatively uncompromised with respect to its unimanual counterpart, whereas the secondary hand seems to move a significantly lesser distance than its unimanual counterpart (right hand) in all trials. Furthermore, although the primary hand’s Dpv is not dependent on task difficulty (similar to the unimanual condition), the ratio of the secondary to the primary hand’s Dpv (DFR) varies significantly with task parameters. This implies that while the primary hand movement may be uncompromised while performing another concurrent task, secondary movement is coupled to the primary movement in a task-specific manner.

3.4.3. Variation of DFR with eye-hand coordination strategies

Both DFR and the eye-hand coordination strategy varied significantly with task difficulty in bimanual tasks. In the selective gaze strategy which is observed when target tolerance is large and inter-target distance is small, both the primary and secondary hand movements are initiated together, reach peak velocity together, and also terminate simultaneously. Both movements are completed while gaze remains on the primary target, and no gaze transition to secondary target occurs. In this case, DFR ~ 1 => the primary and secondary hands have traveled almost equal distances to their respective targets until the instant of peak velocity.

In the predictive strategy which is observed when both target tolerance and inter-target distance are large, both primary and secondary hand movements are initiated together, reach peak velocity simultaneously, and also terminate synchronously. However, this is different from the selective strategy as a gaze transition occurs from primary to secondary target, and this gaze transition occurs before completion of the primary movement. In this case also, the secondary hand travels almost equal distance as the primary hand to its respective target, at the time of peak velocity (no significant difference between primary and secondary Dpv). The Dgs results further indicate that at the time of gaze transition, the primary and secondary hands have covered almost equal distances to target.

The intermittent gaze strategy is observed specifically in cases when the object size is large, but target tolerance and the inter-target distance are small. In the condition, both movements are initiated together, reach peak velocities simultaneously, and even terminate simultaneously despite the target tolerance being restrictively small. This is, we believe, enabled by the multiple gaze transitions that occur between the primary and secondary targets during the course of the bimanual movements. In this case, the primary and secondary hands travel almost equal distances to target, when compared at the time of peak velocity.

In the terminal strategy conditions, when the target tolerance is small, although primary and secondary hand movements are initiated together, and reach their respective peak velocities simultaneously, they terminate at different times. The gaze transition from primary to secondary target occurs after completion of the primary hand movement. In this case, the secondary hand has traveled significantly lesser distance to target than the primary hand at the time of peak velocity. When the inter-target distance increases from 30 to 200 mm, the secondary hand travels even lesser distance to target until the time of peak velocity, when compared to the primary hand. This is found to correlate well with the distances moved by the secondary hand up to the time of gaze shift: the trials in which the secondary hand travels a greater distance to target up to the time of peak velocity are those in which the secondary hand has also traveled a greater distance to target up to the instant of gaze shift. Hence, just as the secondary hand travels less distance to target up to peak velocity as the inter-target distance increases, correspondingly, it also travels lesser distance to target up to the instant of gaze shift as the inter-target distance increases.

From the nature of distances moved by the hands during the acceleration phases and the distances left to target at the time of gaze shifts in the different strategies, it appears that the peak velocity of the secondary hand is anticipatorily scaled, based on task difficulty, so that the terminal phases of movement can be performed with the target in foveal vision. It is important to note here that during the first 30 practice trials, most subjects do not exhibit such “scaling” of their secondary hand velocities during the acceleration phases. They seem to move similar distances with both primary and secondary hands during the initial acceleration phases in the practice trials. As a result of this, the secondary hand exhibits a clear “hovering” phase prior to its terminal correction phase, in which it comes to a complete stop as the primary hand is completing its movement to target, since foveal vision of its target is not available.

In contrast, during the well-practiced experiment trials, the same subjects scale their secondary hand peak velocity such that the secondary hand smoothly slides into its corrective phase, as the primary hand completes its task and vision becomes available. This smooth transition avoids the extra hovering phase exhibited during the practice trials, lending further support to our hypothesis that the motor system benefits from an anticipatory scaling of the secondary hand peak velocity, in terms of both movement time and additional number of sub-movement phases. This suggests that subjects may have adopted different movement strategies based on the predictability of visual feedback. This hypothesis that the subjects modify their movement characteristics based on their expectations about the availability of visual feedback is in accordance with Jakobson et al.’s observation (1991) that kinematic movement variables were affected by task constraints including visually based estimates of object size and movement distance.

Thus, in high-precision bimanual movements, spatial coupling seems to be compromised in favor of temporal coupling. This could be either because temporal coupling of the two hand movements ensures optimal sharing of common resources such as vision, or because temporal coupling relies on proprioceptive mechanisms, rather than visual feedback mechanisms or because temporal coupling could reduce “cognitive” workloads.

CHAPTER 4

EYE-HAND COORDINATION IN ASYMMETRIC BIMANUAL TASKS: TEMPORAL AND SPATIAL ASPECTS

4.1. Introduction

Coordinated bimanual rhythmic movements are generally common and easy to perform. However, when the movements become asymmetric, they become difficult to perform and are often characterized by a high degree of interference based on the coordinating tendencies of the limbs (Franz 1997, Franz et al. 1991). Breaking the natural tendency of the limbs to adopt identical roles while making bimanual movements requires a great deal of effort and attention (Peters 1994).

Studies on the effect of handedness on bimanual movements have suggested that there is an inherent asymmetry to movements that is grounded in handedness preferences (reviewed in Peters 1994). For example, in tasks that require the hands to perform different but complementary patterns, participants generally elect to use their preferred hand for the more demanding task and to use their non-preferred hand in a supporting role (Peters 1994). In tasks that require the hands to perform more similar patterns, performance asymmetries are observed across a range of tasks in which the movements performed by each hand vary in force (Welch 1898), direction (Walter and Swinnen 1990), or frequency (Ibbotson and Morton 1981; Jeeves et al 1988; Peters 1985). Studies have also suggested that the preferred hand leads in a range of symmetric tasks that require the two hands to perform the same pattern. Such tasks include circle drawing (Summers et al 1995; Swinnen et al 1996), ellipse drawing (Stucchi and Viviani 1993), and pendulum swinging (Amazeen et al 1997; Riley et al 1997; Treffner and Turvey 1995, 1996). Although the differences may be subtle, it is clear that the hands do not perform strictly identical roles during bimanual coordination.

Across tasks, the asymmetries associated with handedness have been equated with an attentional symmetry in which participants naturally devote more attention to their preferred hand (Peters 1981, 1994). That is, the hypothesis is that asymmetries in the allocation of attention underlie performance asymmetries. This hypothesis is supported by Amazeen et al 1997 and Riley et al 1997, who observed participants performing a bimanual coordination task in which they swung pendulums simultaneously with their right and left hands. The direction of attention was manipulated by placing paper targets over one of the hands. The targets forced participants to attend to the task performed by that hand. Results showed that participants tended to lead with the hand that was tapping the targets. Both attention and handedness, then, appeared to produce the same phase lead in coordinated rhythmic movements.

The previous chapters have suggested that the handedness effect described here may be reflected in an asymmetry in the feedback processing demands of the two hands. Even in symmetric bimanual transfer tasks in which movement kinematics appeared to be identical, there was a systematic preference to devote initial attention to the left hand's task. Although the coupling of movement parameters varied as a function of task difficulty, the effect of the fundamental left-right asymmetry in the differential coupling of the hand movements (performance symmetry/asymmetry) could not be clearly understood since the task constraints for both hand movements were identical.

Since the effects of primary task difficulty could not be decoupled from those of secondary task difficulty using symmetric bimanual task constraints, asymmetry was introduced in the task parameters in order to better understand how each affects coordination and movement kinematics. The asymmetric bimanual trials were analyzed separately depending on whether the asymmetry was in object size or target tolerance. Some of the main aims of introducing this asymmetry were to study the differences in performance of the left and right hands as both primary and secondary hands, and try to understand:

(i) why subjects preferred certain modes of movement in symmetric bimanual conditions over other possible movement schemes (for e.g., left hand preference for primary task performance when both task difficulties are perceived to be the same)

(ii) the reasons for evolution of specific eye-hand coordination patterns with learning (terminal vs. predictive/selective)

(iii) how the CNS organizes higher-level control of the entire movement – pre-planned vs. online control aspects, temporal vs. spatial characteristics, integrating the multiple modes of available feedback (foveal visual, peripheral visual and proprioception considered)

4.2. Methods

Six right-handed individuals, four male and two female, aged 20-30 years, participated in this experiment as volunteers. All participants were naïve to the purpose of the experiment, with no prior experience at the specific tasks. They had normal vision and were free from neurological and musculo-skeletal disorders. The experiment was approved by the Institutional Review Board of the University of Michigan and all participants signed an informed consent form.

4.2.1. Experimental setup

The experimental task consisted of transferring two objects, one with the left and the other with the right hand, from specified initial positions to target locations. Two pairs of light weight cylindrical objects, of height 120 mm, and diameters 8mm (obj 1), and 44 mm (obj 2) were used in the study. The weights of the objects were 8 gm and 60 gm respectively. The target diameter was defined with respect to the object diameter. For each object, the following two target tolerances were defined:

1. Target diameter = object diameter + 0mm (tol1)
2. Target diameter = object diameter + 45mm (tol2)

The object-to-target distance was set at 400mm for all trials. Apart from object size and target tolerance, the inter-target distance i.e., the distance of separation between the pair of targets was also varied. Distance between the pair of targets, defined as the distance between the two closest points on the target circles, was either 30 or 200mm, as shown in Fig 1. The initial object and final target locations were displayed as images on a 52” flat-screen TV placed horizontally at each subject’s elbow height (Fig 4.1). Subjects were seated in front of the TV such that the screen centerline was aligned with their mid-sagittal plane. The near edge of the screen was placed 250mm away from the participant's pelvis. The screen's aspect ratio of 16/9 translated to a frame resolution of 1920 X 1080. At the initial locations, the centers of objects were 25mm away from the near-edge of the screen and ~ (380 + 0.5*inter-target distance + 0.5*target tolerance)mm from the mid-sagittal plane, while the target centers were positioned along a horizontal line that was 127mm away from the line joining the initial object centers. The centerline of the screen was used as the axis of symmetry to place the objects and targets. All trials were designed such that any hand's transfer task consisted of moving objects from initial to final locations, both of which were always located on the same side of the subject's mid-sagittal plane as that of the corresponding hand. An image file, based on specifications for the object and target sizes and their respective locations, was created for each task condition. The sequence of image files was randomized and presented using a software interface to simulate each trial during the experiment.

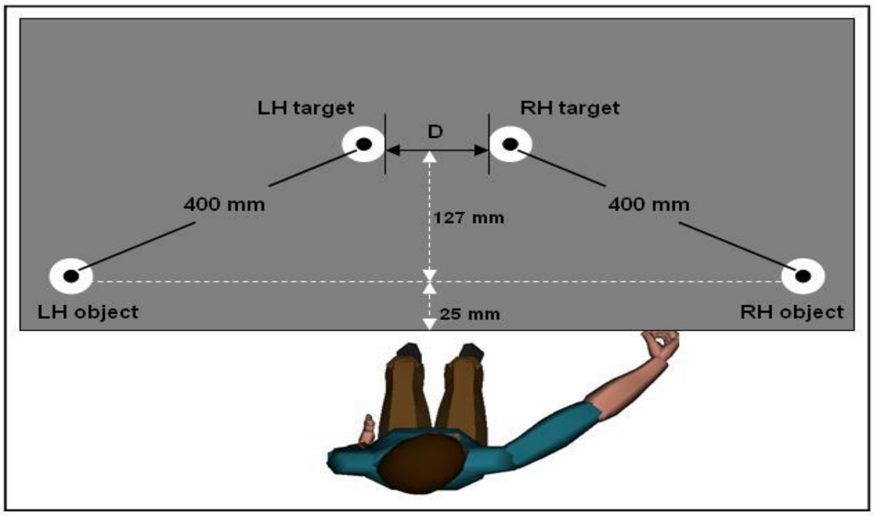


Fig. 4.1: Experimental setup showing the object and target locations on LCD screen

4.2.2. Movement recording

An eight-camera Qualisys® motion capture system was used to record kinematic data sampled at 60 Hz. Passive, reflective markers were placed on selected body landmarks to record the subject's hands, arms, torso and head movements as illustrated in fig 4.2. Markers were placed on important body landmarks: head (3), left and right shoulders (2), elbows (2), wrists (2), sternum (3) and pelvis (2). Eye movements were recorded simultaneously using a head mounted eye tracking system

(ASL eye trac 6.0®). The direction and point of gaze were also monitored on line on a video screen (Fig 2). Both gaze and body movement signals were synchronized and recorded at 60 Hz. Video images of all trials were recorded using a JVCGR-DX97 video camera that was also synchronized with the movement data recording system.

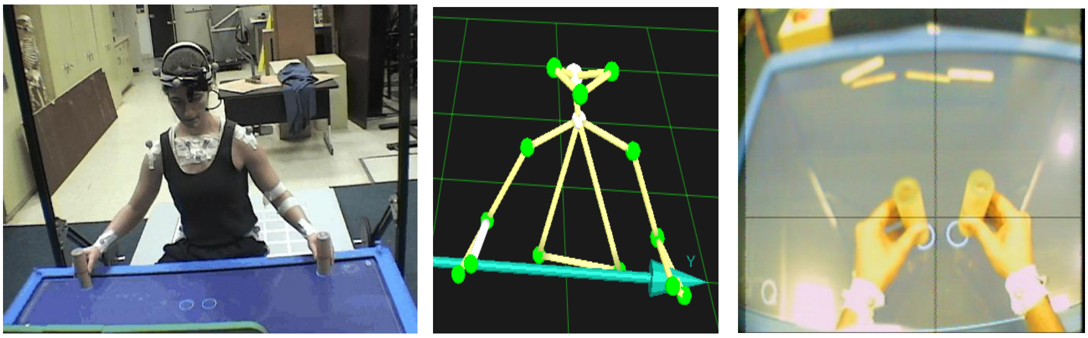


Fig. 4.2: (a) Motion capture and eye-tracker systems setup **(b)** Body linkage system **(c)** Example of a scene from the video camera mounted on the eye tracker: cross hairs indicate the point of gaze

Gaze data was obtained using a two-step calibration procedure. The first step was to calibrate the eye-in-head position using the standard 9 point calibration procedure provided by ASL. During this procedure, the head position was fixed using a bite-bar attached to a fixed frame. The calibration targets were presented on the actual work plane on the LCD screen surface. The next step was to calibrate the eye-in-space (gaze) orientation. The subject was asked to fixate five points sequentially while the head was free to move. The eye tracker measured the subject's eye-in-head signal for each target, while head position was simultaneously recorded using the motion capture system, to obtain the head-in-space signal. The spatial coordinates of each target were computed using the motion capture system. These datasets were combined to develop an offline calibration procedure to obtain gaze orientation (eye-in-space signal). Thus, to analyze gaze-hand coordination in a common frame of reference, the data pertaining to the line of sight was projected to the work plane defined in the real world coordinates of the motion capture system.

4.2.3. Procedure

Subjects were instructed to move a pair of objects, one with their left and the other with their right hands, from their respective initial positions to specified target locations. The left hand always picked the object on the left and moved it to the left target location, and vice versa for the right, i.e., the task did not require any crossing over of the two hands. No explicit instruction was provided to the subject about the expected sequence of movements and no constraints were imposed on speed of movements either.

The subjects started each trial with the objects already grasped in their hands, and the eyes fixating a target placed in the mid-sagittal plane at eye level. This initial eye-position was standardized so that the quality of visual information about the targets was the same for all subjects at the start of each trial. This visual target was fixed in the mid-sagittal plane so that the subject’s first gaze shift during the trial could be clearly defined. On receiving the cue to start, the objects were transferred to the target locations, and held there until the end of the trial without changing hand positions, but gaze was returned to the initial target fixation, after the end of hand movements. Once the transfer task was complete, the subjects continued to hold the objects at the target position until the end of the trial. Kinematic parameters were defined to identify the end of hand movements in each trial. However, for the gaze data, returning the gaze to the initial-home position identified the end of gaze movements in each trial. A pinch grasp was used to hold all objects. Thumbprints were placed on all objects to standardize the grip locations. Movement speed was not specifically constrained, and subjects were asked to move at a comfortable pace to complete the task. The only constraint imposed on task-performance was zero error tolerance in the accuracy of positioning.

Since the pilot studies indicated the development of consistent eye-hand coordination strategies with learning, experimental data collection was initiated after 100 practice/learning trials. The set of 100 practice trials were picked randomly from the actual experiment trials and the subjects were not aware that these practice trials were excluded from the analysis. Each condition was repeated thrice during the experiment trials. All conditions were randomized and inter-trial intervals were of approximately 15 seconds. Before each trial, the subject was allowed to see the locations of the objects and the targets. If the accuracy constraints were not met in any of the trials, those corresponding trials were repeated at the end of the experiment.

For trials in which the target size was larger than the object size, the objects had to only be placed within the limits of the target area and did not have to be centered. The objects had to be moved and brought in vertically. The participants were not allowed maneuvers such as pivoting one end of the object at an angle and rolling it in to the target zone, or sliding the objects on the surface of the screen. Adjustments or corrections were not allowed after the object made contact with the surface. In addition, subjects were also instructed to refrain from bracing/supporting their arms on any surface.

4.2.4. Experimental design

Left hand's object size (8 and 44mm) and target tolerance (0 and 45 mm), right hand's object size and target tolerance, and the distance between targets (30 and 200 mm) were the independent variables, which yielded a 4X4X2 mixed level factorial design.

Three replicates were used for each condition. Although all these parameters were varied, the diagonal elements of each square matrix corresponding to one level of inter-target distance were analyzed in the symmetric bimanual sections, and only results pertaining to the off-diagonal elements are analyzed in this chapter. The off diagonal elements of the experimental matrices corresponded to those trials in which the bimanual movements were "asymmetric" in requirement. This asymmetry was of three main types:

1. Asymmetry in object size: Left and right hand objects were of different sizes, although the target tolerance (with respect to the object size) was the same in both cases
2. Asymmetry in target tolerance: Left and right hand objects were of the same sizes, but the target tolerances were different for the 2 different movements
3. Asymmetry in both object size and target tolerance: Both left and right hand object sizes and target tolerances were different between the two hand tasks

Thus a total of 72 recorded trials ([32-8] conditions X 3 repetitions) were analyzed for each participant. The labeling convention adopted to identify the trial type was:
"LH object – LH target tolerance – distance between targets – RH target tolerance – RH object"

According to this convention, a trial of type “8-0-200-45-8” means that LH and RH object sizes are 8mm, target tolerances are 0 and 45 mm respectively for the left and right hand targets (i.e. the target diameters are 8 and 53 mm), and the distance between the two targets is 200 mm.

4.2.5. Data analysis

The three dimensional data from the motion capture system was filtered using a second order, low pass Butterworth filter with a cut-off frequency of 6 Hz. The kinematic data from the markers placed on the wrists were used to calculate the onset and end times of movements. Movement onset corresponded to the first instant at which the magnitude of tangential velocity of the wrist marker exceeded 5 mm/sec. The end of movements was defined as the first instant after the occurrence of peak velocity, at which the object came in contact with the LCD screen surface (observed from synchronized video recordings of the trials), and the magnitude of tangential velocity of the wrist marker fell below 5 mm/sec. This dual constraint was used to define the end of movements since it was observed that in some trials, when one hand entered its final task-completion phase, the other hand would hover at an intermediate location of its trajectory. As the hand velocity fell below the defined threshold of 5mm/sec in such cases, the velocity condition alone was insufficient to define the end of movements, and the constraint of hand reaching the target was added, in order to eliminate possible confusions about the end of a hand movement.

In bimanual trials, the hand that moves to the target which is fixated first during the experiment is defined as the “primary” hand, and the other hand is referred to as the “secondary” hand in this study. The distances traveled by each hand from the time of movement onset up to the instant of peak velocity (Dpv) were computed by integrating the speed, from movement onset up to Tpv. This was expressed as a percentage of the total distance of movement (computed by integrating speed profiles over the total time of movement):

$$\text{Dpv of a hand} = \frac{\text{Distance traveled up to instant of peak velocity}}{\text{Total distance of movement}} *100$$

The performance of the primary hand in these bimanual trials was also compared to the performance of the same hand in a unimanual task configuration.

Further, in bimanual trials, since we were interested in the performance of the secondary hand relative to the primary hand, the ratio of Dpv of the secondary hand to the Dpv of the primary hand, defined as 'distance fraction ratio' (DFR), was computed for the different tasks.

$$DFR = \frac{\%Dpv_{\sec ondary}}{\%Dpv_{primary}}$$

The distance remaining to target at the instant of gaze shift from primary to secondary hands was also computed and expressed as a percentage of the total distance of movement (Dgs):

$$Dgs = \frac{\text{(Total distance to target – Distance up to instant of gaze shift)}}{\text{Total distance to target}} * 100$$

4.3. Results

4.3.1. Asymmetry in object size

Object-asymmetry refers to those bimanual trials in which the two objects (to be moved by the left and right hands to their corresponding target locations) were of different sizes, but the target tolerance at each location was the same between the two hands. There were four main trial types in this category with 1 object size in each hand, for each level of target tolerance and inter-target distance:

1. 8-0-30-0-44
2. 8-0-200-0-44
3. 8-45-30-45-44
4. 8-45-200-45-44

Four more trial types were obtained by reversing the object sizes between the hands:

5. 44-0-30-0-8
6. 44-0-200-0-8
7. 44-45-30-45-8
8. 44-45-200-45-8

Thus, a total of 8 trial types, with 3 repetitions each, were performed by each of the 6 subjects in the object-asymmetry category.

Onset, time-to-peak velocity and end times of hand movements

Typical velocity profiles of the left and right hands of a subject, in a bimanual trial of type 8-0-30-0-44, are illustrated in fig 4.3. Repeated measures ANOVA analyses were performed on the time lag in movement onset between the left and right hands (O_{L-R}), difference in time-to-peak velocities of left and right hands (P_{L-R}) and difference in end-times of left and right hands (E_{L-R}). The analyses showed that task conditions did not have a significant effect on the magnitude of the time lag in movement onset between the two hands ($|O_{L-R}|$). As indicated by table 4.1, neither the main effects nor the interactions of object sizes, target tolerance and the distance between targets had a significant influence on $|O_{L-R}|$. Similarly, the task conditions did not significantly affect the magnitude of difference in time to peak velocities of the left and right hand ($|P_{L-R}|$) either. It was also observed that task conditions did not significantly affect the order in which the left and right hands started the movements or reached peak velocity. Thus, the task conditions did not have a significant effect on the sign of time lags in both movement onset and time to reach peak velocity ($P > 0.5$). The average lag, or average absolute difference in movement onset times between the left and right hands ($|O_{L-R}|$), collapsed across all conditions and subjects was 30± 17 ms. The average absolute difference in times to peak velocity of the left and right hands ($|P_{L-R}|$) across all conditions was 31± 28 ms. The ANOVA analyses also indicated that there was no significant learning effect for any of the factors.

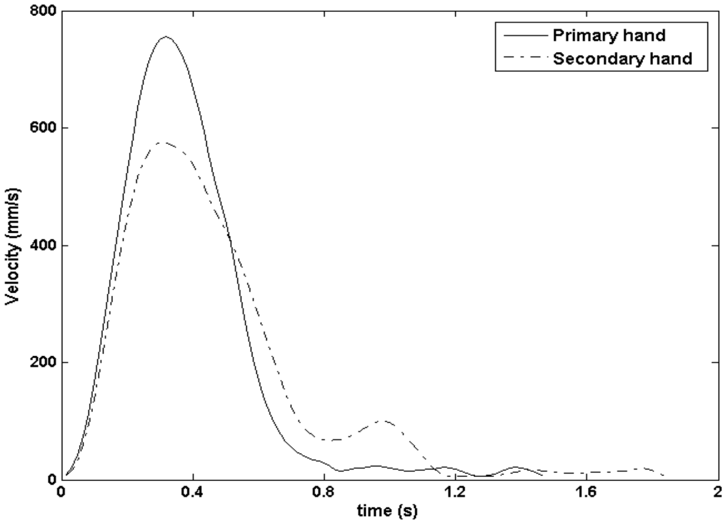
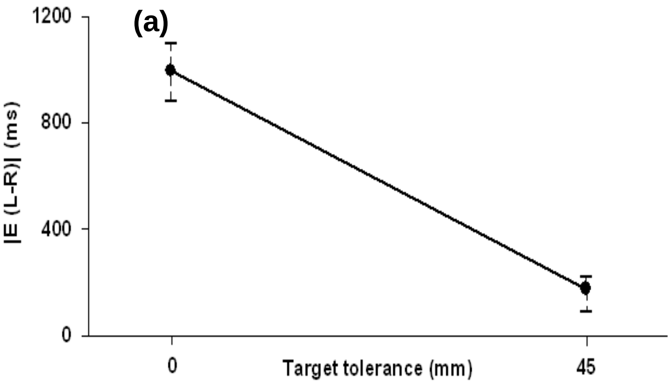


Fig. 4.3: Typical velocity profiles of primary and secondary hands of a subject in a bimanual trial of type 8-0-30-0-44

Table 4.1: Repeated Measures ANOVA: effect of object-asymmetric task conditions on $|O_{L-R}|$, $|P_{L-R}|$ and $|E_{L-R}|$

General Linear Models (alpha = 0.05)		$\mathbf{|O_{L-R}|}$		$\mathbf{|P_{L-R}|}$		$\mathbf{|E_{L-R}|}$	
Factor	**DOF**	**F stat**	**P-value**	**F stat**	**P-value**	**F stat**	**P-value**
Object sizes	1	1.7	0.20	0.62	0.44	3.2	0.08
Target tolerance	1	0.92	0.34	0.55	0.46	24.56	<0.001
Distance between targets	1	1.51	0.23	0.93	0.34	17.82	0.001
Object size*Target tolerance	1	0.39	0.54	1.57	0.22	4.01	0.05
Object size*Distance between targets	1	0.69	0.41	0.09	0.77	2.11	0.15
Target tolerance*Distance between targets	1	0.15	0.7	0.60	0.44	11.81	0.001
Object size*Target tolerance*Distance between targets	1	0.38	0.54	0.99	0.32	4.11	0.05
Error	40						

Although the left and right hand movements in these bimanual trials started and reached peak velocities at similar times, the difference in end-times of the two hands varied with task condition. Target tolerance and inter-target distance had significant effects on $|E_{L-R}|$, whereas object-size couplings did not significantly influence $|E_{L-R}|$. $|E_{L-R}|$ decreased with increase in target tolerance ($P<0.001$) and decrease in inter-target distance ($P = 0.001$). The interaction effect of target tolerance and inter-target distance on $|E_{L-R}|$ was significant ($P = 0.001$), whereas all other factor interactions were not significant (table 4.1). Although $|E_{L-R}|$ increased considerably with increase in inter-target distance at zero target tolerance, the effect of inter-target distance on $|E_{L-R}|$ was not significant when target tolerance was increased to 45mm. The main and interaction effects of target tolerance and inter-target distance on $|E_{L-R}|$ are illustrated in fig 4.4.



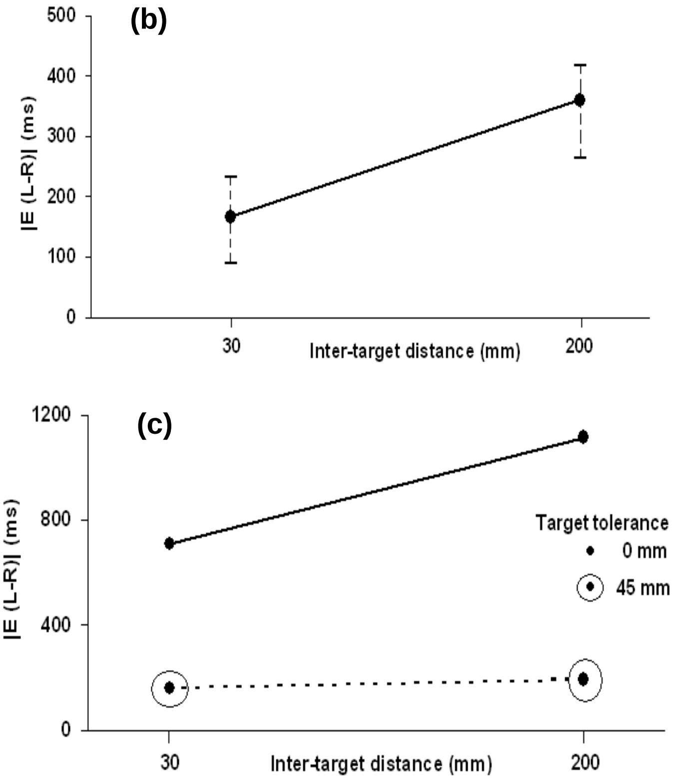


Fig. 4.4: (a) Main effect of target tolerance on $|E_{L-R}|$; **(b)** Main effect of inter-target distance on $|E_{L-R}|$; **(c)** Interaction effects of target tolerance and inter-target distance on $|E_{L-R}|$

Thus, neither the main effect nor any interactions of object size couplings of the left and right hands had any significant effect on $|E_{L-R}|$. Asymmetry in object size seems to have no effect on the onset, time-to-peak velocity and end times of hand movements.

Hand precedence in termination phases

In 83% of object-size asymmetric bimanual trials, the left hand preceded the right hand to complete its placement first (although there was no significant hand precedence in the initial phase of the movement up to peak velocity). This phenomenon of left hand precedence was not influenced by task condition or inter-subject differences. In the subsequent analysis, the left hand is referred to as the primary hand, and the right hand as the secondary hand.

Gaze strategies

The coordination of gaze and hand movements was investigated in terms of the temporal coordination between gaze orientation entering and exiting land-marked target zones of the two hands and each hand's movement specific kinematic events.

Two main gaze strategies were observed:

1. Terminal gaze strategy: Gaze is directed towards one of the first, and after completion of placement of the corresponding object, moves to the other target;

2. Predictive gaze strategy: Gaze is directed towards one target initially, but then redirected to the other target even before the completion of placement at the initially foveated target location;

Irrespective of the inter-target distance and object-size couplings, subjects adopted the terminal gaze strategy in ~89% of the trials in which target tolerance was 0mm, and the predictive gaze strategy was preferred in ~83% of the trials in which target tolerance increased to 45 mm. The other two gaze strategies (selective and intermittent) that were observed in symmetric bimanual tasks were not observed in asymmetric conditions.

Distance traveled by primary and secondary hands up to instant of peak velocity

Dpv is the distance traveled by the hand from the time of movement onset to the time of peak velocity, expressed as a percentage of the total distance of movement.. The primary hand (left hand's) Dpv does not significantly change with task condition, i.e. object sizes ($P = 0.23$), target tolerance ($P = 0.34$) and inter-target distance ($P > 0.5$), as shown in fig 4.5. In addition, fig 4.6 shows that the average Dpv of the primary hand (left hand) is similar to the left-hand unimanual Dpvs of each subject.

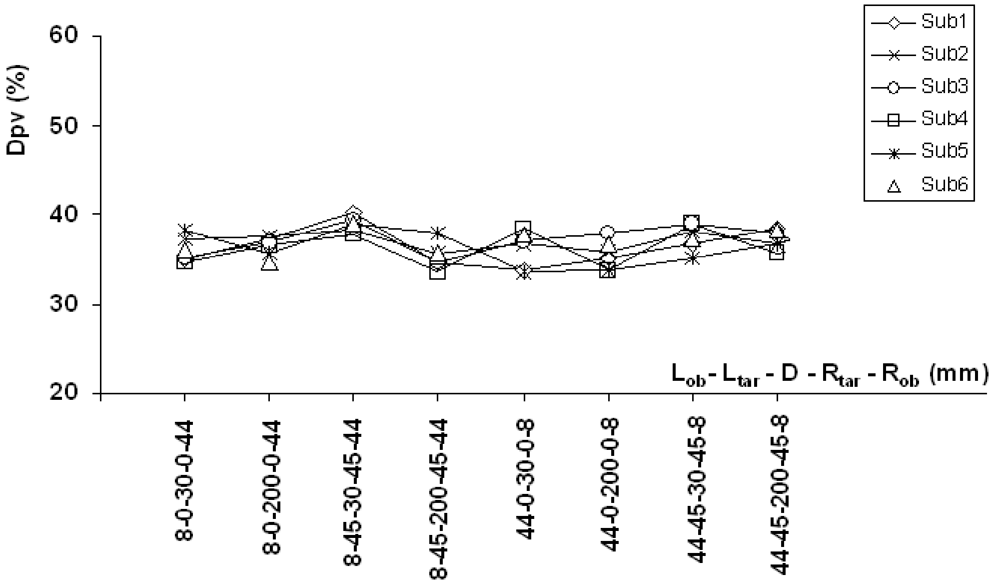


Fig. 4.5: Dpv of primary hand of all subjects as a function of task condition

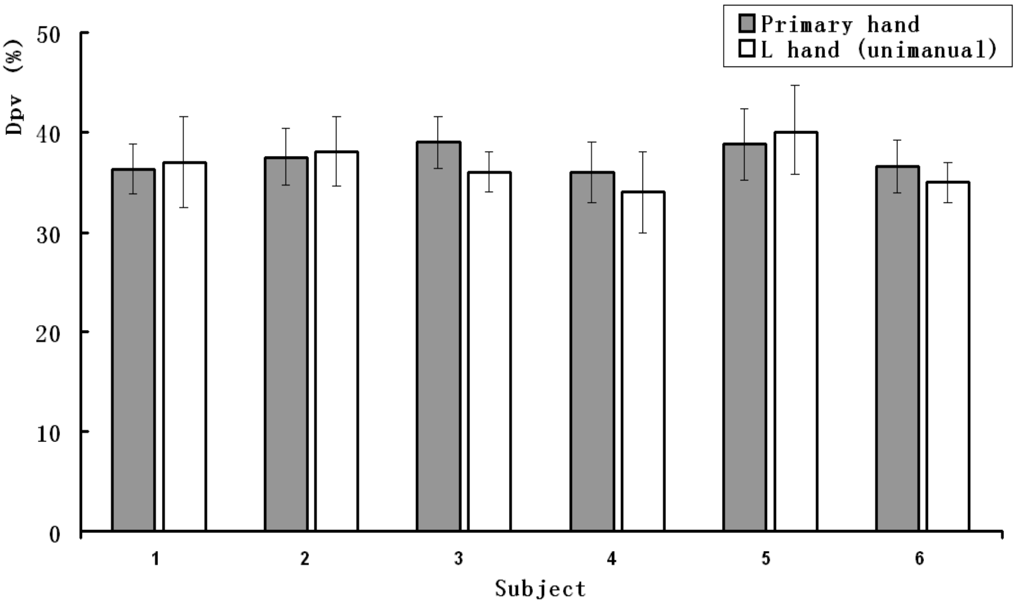


Fig. 4.6: Comparison of Dpvs of left hand in unimanual and bimanual trials

However, the Dpv of the secondary hand, relative to the Dpv of the primary hand varies with each task condition. The distances traveled by the primary and secondary hands up to the instant of peak velocity in one typical subject are illustrated in fig 4.7.

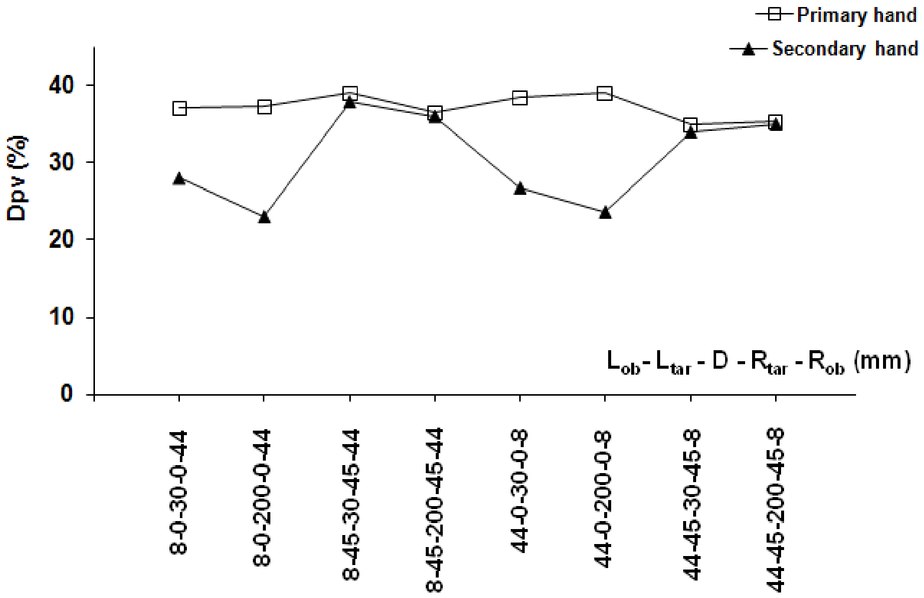


Fig. 4.7: Typical Dpvs of primary and secondary hands of one subject in different bimanual conditions

When the DFR (ratio of the Dpv of secondary to Dpv of primary hand) was analyzed using a repeated measures ANOVA, main and interaction effects of target tolerance and inter-target distance influenced DFR significantly (table 4.2). The effect of object size asymmetry on DFR was not significant.

Table 4.2: Repeated Measures ANOVA - effects of task condition on Dpv of primary hand & DFR

General Linear Models (alpha = 0.05)		**Dpv**		**DFR**	
Factor	**DOF**	**F stat**	**P-value**	**F stat**	**P-value**
Object sizes	1	0.271	0.606	2.147	0.151
Target tolerance	1	1.834	0.183	105.8	<0.001
Inter-target distance	1	0.073	0.789	6.256	0.017
Object size*Target tolerance	1	0.006	0.937	4.318	0.044
Object size*Inter-target distance	1	0.424	0.519	3.167	0.083
Target tolerance*Inter-target distance	1	0.097	0.757	59.25	<0.001
Object size*Target tolerance* Inter-target distance	1	0.062	0.805	1.111	0.3
Error	40				

Main and interaction effects of target tolerance and inter-target distance from fig 4.8 show that DFR increases with increasing target tolerance and decreases with increasing inter-target distance. However, significant interaction (***P***<0.001) between the two factors indicates that while the effect of inter-target distance is significant for zero tolerance targets, it does not significantly affect DFR when target tolerance is 45 mm.

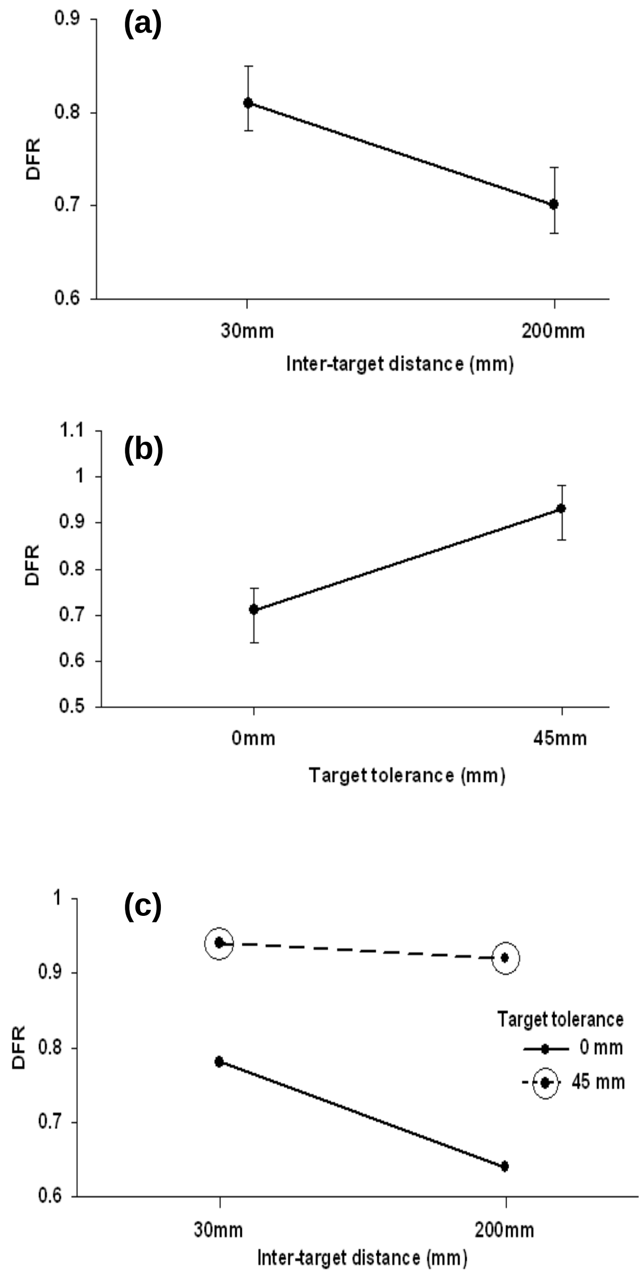


Fig. 4.8: (a) Main effect of target tolerance on DFR **(b)** Main effect of inter-target distance on DFR **(c)** Interaction effect of target tolerance & inter-target distance on DFR

Variation of DFR with eye-hand coordination strategy

The means of DFRs of different subjects in the terminal and predictive strategies are presented in Fig 4.9. Since inter-target distance does not have a significant effect on DFR when the target tolerance is 45 mm, the means of DFR in the predictive strategy (when target tolerance is 45 mm) do not vary significantly with inter-target distance. Hence these have been pooled together in the fig 4.9. However, the means of DFR in the terminal strategy vary significantly with inter-target distance (table 4.2) and are consistently lesser than those of the predictive strategy trials. Hence DFR of terminal strategy trials have been presented separately, based on inter-target distance.

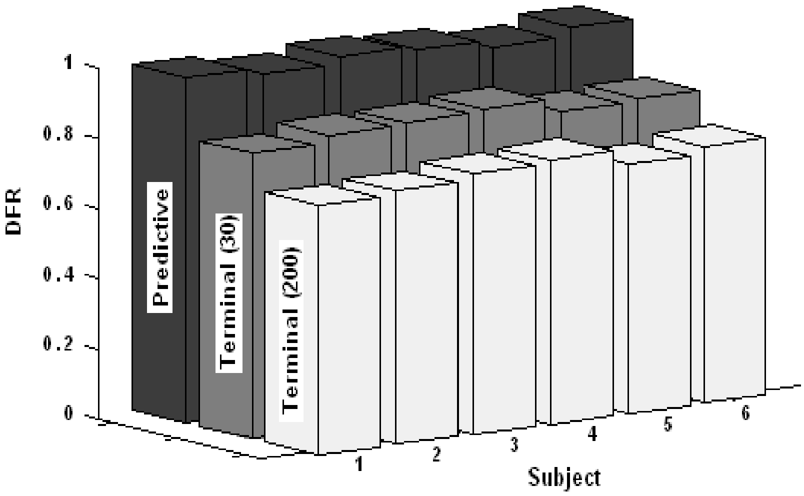


Fig. 4.9: Variation of DFR with different eye-hand coordination strategies

Distance traveled up to instant of gaze shift

The distances traveled by both primary and secondary hands up to the instant when a shift in gaze occurs from the primary to secondary target in bimanual trials were computed. In trials where subjects adopt predictive strategy, although the distances traveled by the primary and secondary hands up to the instant of gaze shift vary between subjects, both the primary and secondary hands seem to have traveled almost equal distance to their respective targets at the time of gaze shift for each subject, irrespective of object sizes and inter-target distances (fig 4.10). Fig 4.11 shows the Dgs of the secondary hand during trials in which the terminal gaze strategy was used. Since the gaze transition from primary to secondary target occurs after the primary hand reaches its target in this strategy, the Dgs of the primary hand is always zero and is hence not plotted in the figure. In the trials in which subjects adopt the terminal strategy of movement, Dgs of the secondary hand is higher when the inter-target distance is 200 mm, than when it is 30 mm. Thus, subjects have traveled more distance to the secondary target by the time gaze shift occurs in cases when inter-target distance is small, when compared to those cases in which inter-target distance is higher. With the terminal strategy trials, a comparison of the mean Dgs of the trials in which inter-target distance was small (30 mm) vs. those in which it was large indicated that they were significantly different ($\boldsymbol{P} < 0.001$).

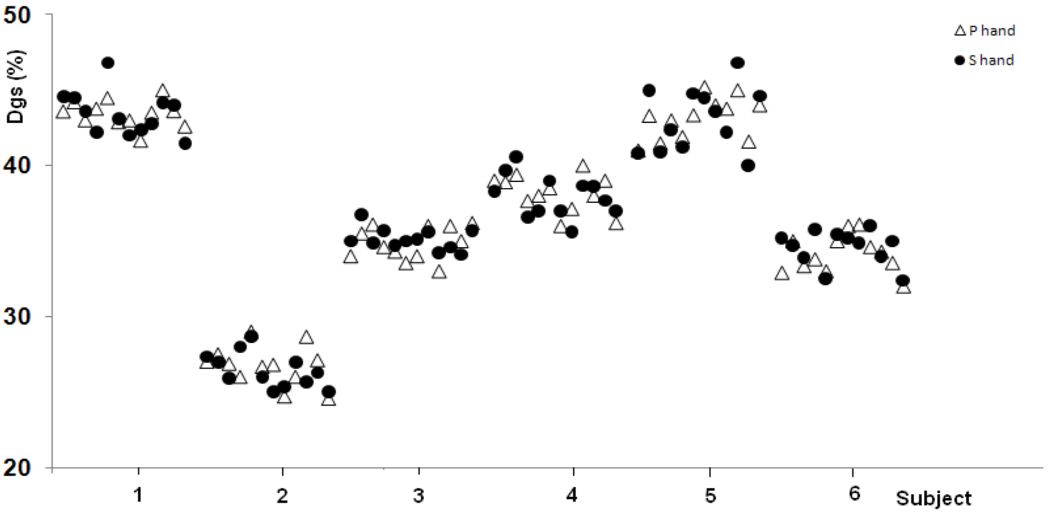


Fig. 4.10: Dgs of primary and secondary hands in trials corresponding to predictive gaze strategy

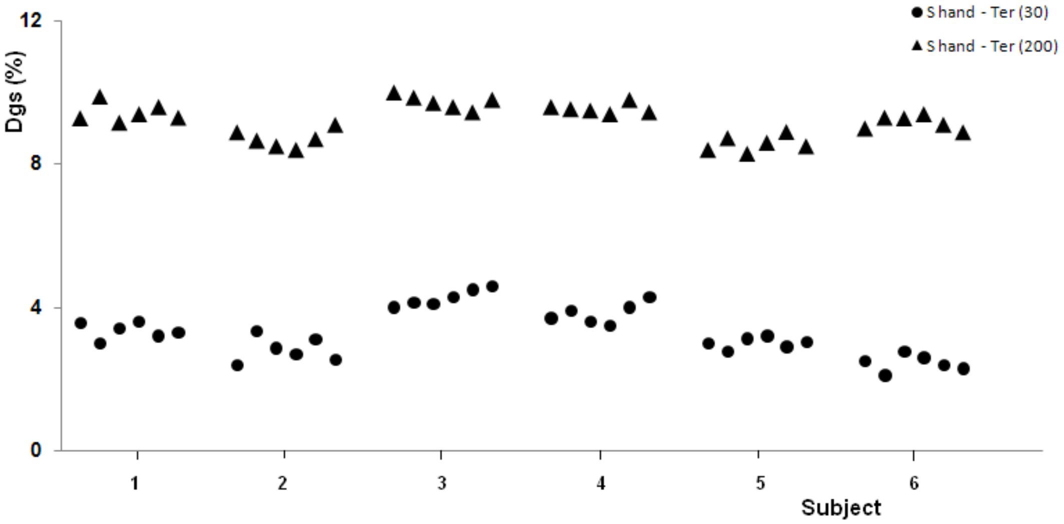


Fig. 4.11: Dgs of secondary hands in trials corresponding to terminal gaze strategy, classified based on inter-target distance

Correlation between Dpv and Dgs of the secondary hand during terminal gaze strategy

Correlation coefficient, computed between Dpv and Dgs of the secondary hand during trials in which subjects adopted the terminal gaze strategy, was found to be -0.81. This indicates that when the secondary hand travels a greater distance up to peak velocity, it has subsequently also traveled a greater distance up to its gaze shift.

Thus, object-asymmetric bimanual trials seem to be similar to their corresponding symmetric bimanual trials in terms of left-hand preference for being chosen as the primary hand and the differences in onset time, time to peak velocities and end of movement times between the two hands. If the trials with intermittent gaze strategy (subjects made multiple gaze transitions between the primary and secondary targets) are neglected from the symmetric bimanual analysis, then the object-asymmetric trials and symmetric bimanual trials are almost identical in terms of temporal and spatial aspects of eye-hand coordination.

4.3.2. Asymmetry in target tolerance

These were asymmetric bimanual trials in which the two objects to be moved by the left and right hands to their corresponding target locations were of the same size, but the target tolerance at each location was different between the two hands. There were four main trial types in this category, for each object size and inter-target distance:

1. 8-0-30-45-8
2. 8-0-200-45-8
3. 44-0-30-45-44
4. 44-0-200-45-8

Four more trial types were obtained by reversing the two target tolerances between the two hands, i.e.:

5. 8-45-30-0-8
6. 8-45-200-0-8
7. 44-45-30-0-44
8. 44-45-200-0-44

Thus, a total of 8 trial types, with 3 repetitions each, were performed by each of the 6 subjects in the target-asymmetry category. In categories 1-4, the left hand performs the zero-tolerance task, while the right hand performs the 45mm-tolerance task, whereas in categories 5-8, the right hand performs the zero-tolerance task and the left hand performs the easier 45mm-tolerance task.

When there was an asymmetry in target tolerance, in 56% of trials, subjects adopted a terminal gaze strategy in which placement at the zero-tolerance target was completed first, and then placement at the 45 mm tolerance target was completed next, with the gaze shift from primary to secondary target occurring after object placement at the primary target location. In the remaining 44% of trials, a predictive gaze strategy was used such that placement was completed first at the 45 mm tolerance target, followed by placement at the zero-tolerance target. In these trials, a predictive gaze strategy implied that the gaze transition occurred prior to movement completion at the primary target location. Table 4.3 shows the distribution of terminal vs. predictive strategies across different trial conditions and subjects. Adoption of the terminal or predictive strategies seems to be random, both within and between subjects. Neither the task conditions nor the individual subject strategies or any hand-preference seemed to have any significant effect on which eye-hand coordination strategy was used in the trial.

Table 4.3: Distribution of terminal and predictive strategies across all target-asymmetric trials

	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6
8-0-30-45-8	T T P	P T P	P P T	T T T	P P T	T P T
8-45-30-0-8	P T P	P T P	P P T	T T P	P T P	P T T
8-0-200-45-8	T T T	P T P	P P T	T T P	P P T	T P T
8-45-200-0-8	P P T	P T P	P T T	T P P	T P T	T T T
44-0-30-45-44	T T P	P T P	T T T	P P T	T P P	P T T
44-45-30-0-44	P T T	P P T	T T T	P P P	T T T	T P T
44-0-200-45-44	T T P	P P T	T T T	T P P	P T P	T P T
44-45-200-0-44	T T T	T P P	T T T	P P T	T P P	T T P

4.3.2.1. Terminal Gaze Strategy

Onset, time-to-peak velocity and end times of hand movements

Fig 4.12 shows typical velocity profiles of the right and left hands during an asymmetric bimanual trial of type 8-0-30-45-8: Object size is 8 mm for both the right and left hand task, but the left hand task's target tolerance is 0 mm while the right hand task's target tolerance is 45 mm, and the inter-target distance is 30 mm. In the example shown below, both hand movements are initiated together, reach their respective peak velocities simultaneously, but during the deceleration phase of the movements, the left hand completes its placement first and then the right hand completes its placement. The terminal gaze strategy is used such that the gaze transition from the left target to right target occurs only after completion of place movement to the left target.

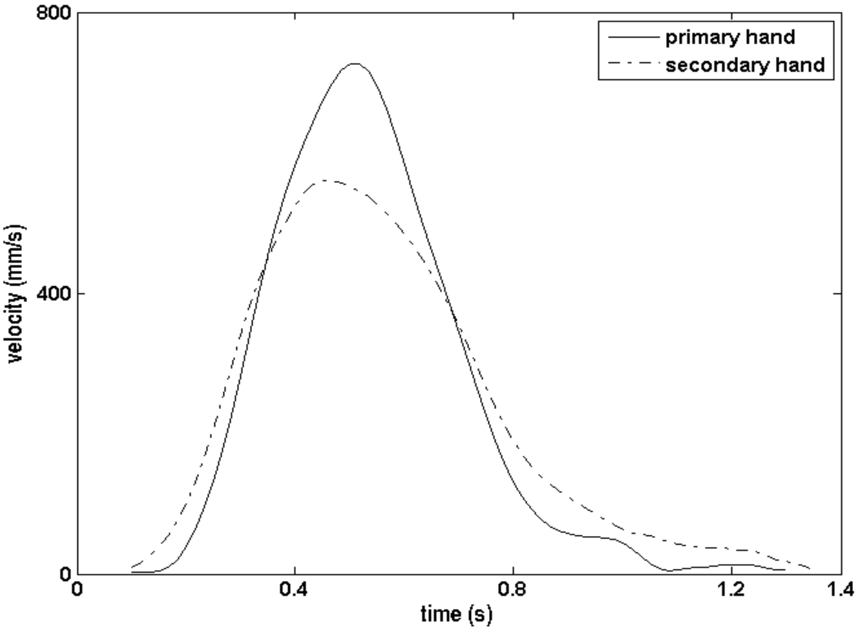


Fig. 4.12: Typical velocity profiles of primary and secondary hands of a subject when terminal gaze strategy is adopted in a target-asymmetric bimanual trial

In such bimanual trials in which target tolerance is asymmetric between the two hands and the terminal eye-hand coordination strategy is used, the two hand movements are initiated together and reach peak velocities simultaneously. The average difference in movement onset times between the left and right hands is 26± 20 ms and the average difference in time-to-peak velocities of the two hands is 39 ± 28 ms. Neither the task conditions nor individual subject differences significantly affected the order in which the left and right hands started the movements or reached peak velocity. Although both hand movements were initiated together and reached peak velocities together, movement to the zero-tolerance target took precedence in execution during the deceleration phase of the movement, followed by movement to the higher tolerance target. The placements of the two objects at their respective target positions were thus always sequential. The difference in end times of the primary and secondary hand movements, both within and between subjects for each trial condition, is shown in fig 4.13.

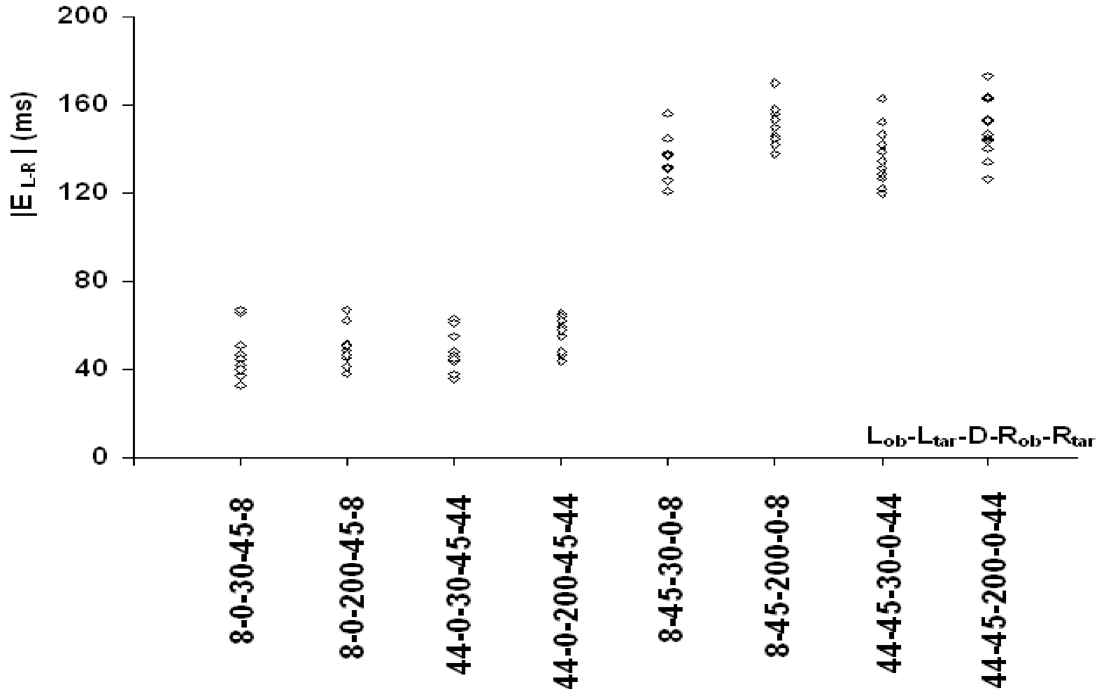


Fig. 4.13: |E L-R| of all subjects in each trial condition

Although the end times between the two hand placements did not vary significantly (***P***>0.5) with object size or inter-target distance, it seems to increase when the primary task is performed by the right hand and the secondary task is performed by the left hand, as against the left hand performing the primary zero-tolerance task. The average difference in end times between the primary and secondary hands when the right hand performs the primary task is significantly higher than the average difference in end-times between the two hands when the left hand performs the primary task (***P***<0.001).

It's possible that this difference in placement times between the two hands varies with which hand performs the primary task because of a fundamental difference in the primary movement-completion times of left vs. right hands. In order to verify if this was the case, or whether the left hand was truly slowing down much more than the right hand during the deceleration phases of the secondary task, the 'time of deceleration' (Tdl) of each movement was computed as the time from the instant of peak velocity to the end of the movement and compared across the different trials in fig 4.14.

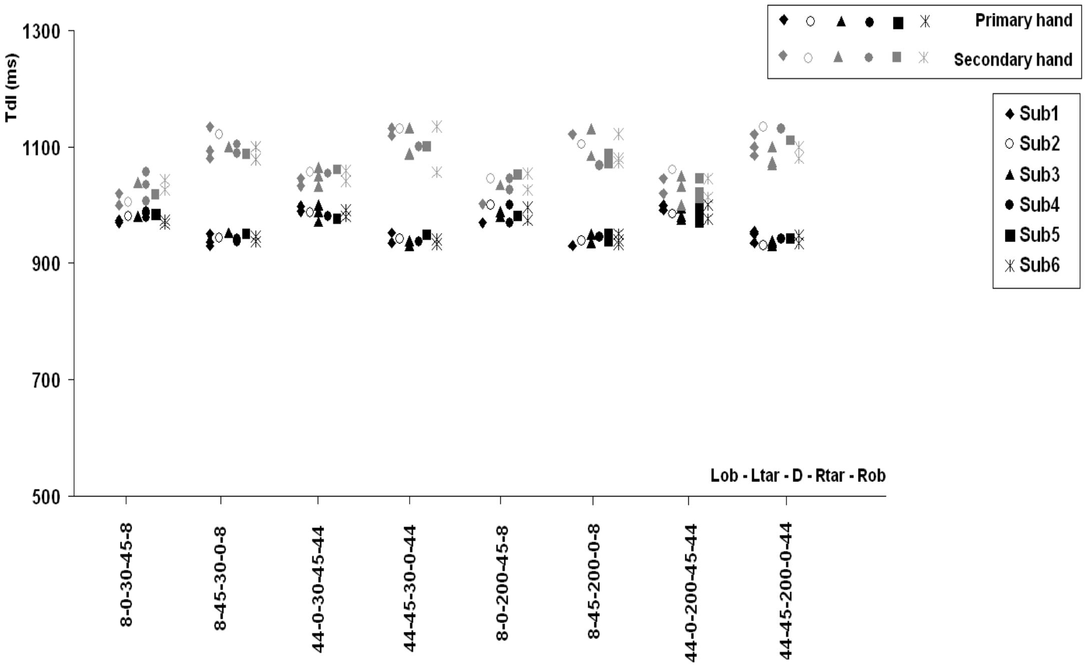


Fig. 4.14: Times of deceleration phase of primary and secondary hand movements (time from peak velocity to end of movement) in different trial conditions

The figure shows that although there is a difference in the primary movement times of the right and left hands, the left hand performing the secondary task has much longer deceleration times than the right hand performing the same secondary task, thus making the total movement time of a bimanual task longer when the right hand is the primary hand and the left hand is the secondary hand, as against the left hand being the primary hand and the right hand being the secondary hand.

Similarly, the distance traveled by each hand up to the time of peak velocity depended on which movement (right hand/left hand) was given precedence in execution during the terminal phases of the movement. Fig 4.15 shows the Dpv of the primary hand of all subjects across the different task conditions.

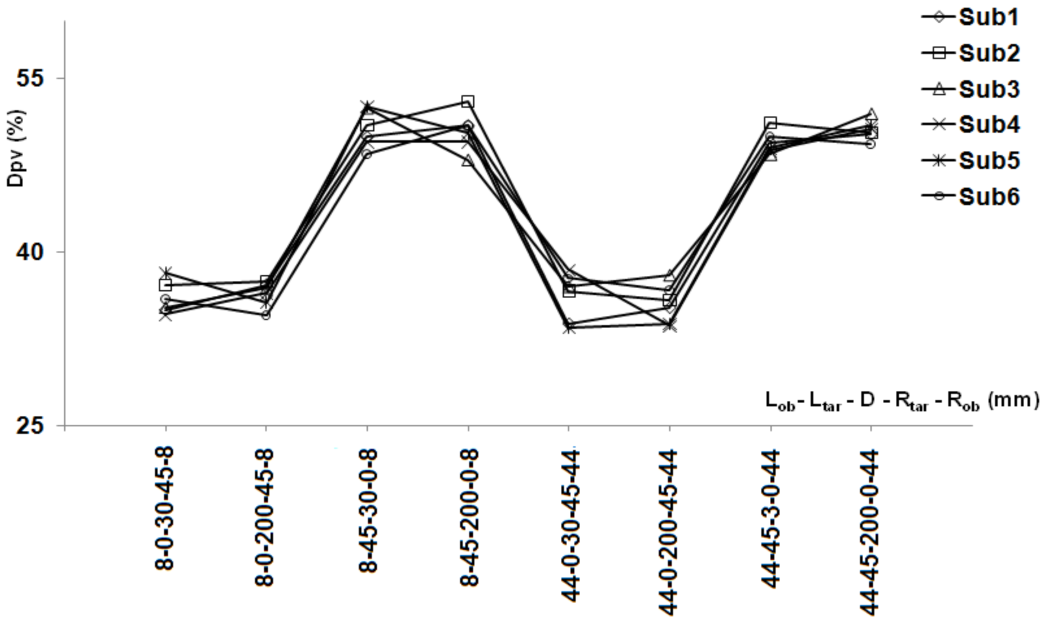


Fig. 4.15: %Distances to target, moved by primary hand up to instant of peak velocity in different task conditions

From the above figure, it can be observed that although the primary hand's Dpv does not significantly change with task conditions for a given hand (left/right), Dpv of the primary hand is higher when the right hand is the primary hand as compared to the left hand being the primary hand. This trend is consistent across all subjects and is in similar to our earlier observations of Dpv of right and left hands in single-handed movements.

Fig 4.16 shows the Dpv of the primary and secondary hand movements of one subject when the primary target was the zero-tolerance target. Within each hand, the secondary hand's Dpv is relatively constant with object size, but decreases with increasing inter-target distance. When comparing the right and left hands performing as secondary hands, the left hand's Dpv are further reduced than the right hand's Dpv for similar task conditions.

The mean DFRs of the secondary hand of all subjects, classified according to object size, inter-target distance and whether the right or left hand is the secondary hand, are presented in table 4.4. Irrespective of whether the right hand is the primary or the secondary hand, its Dpv is always higher than that of the left hand in similar trials.

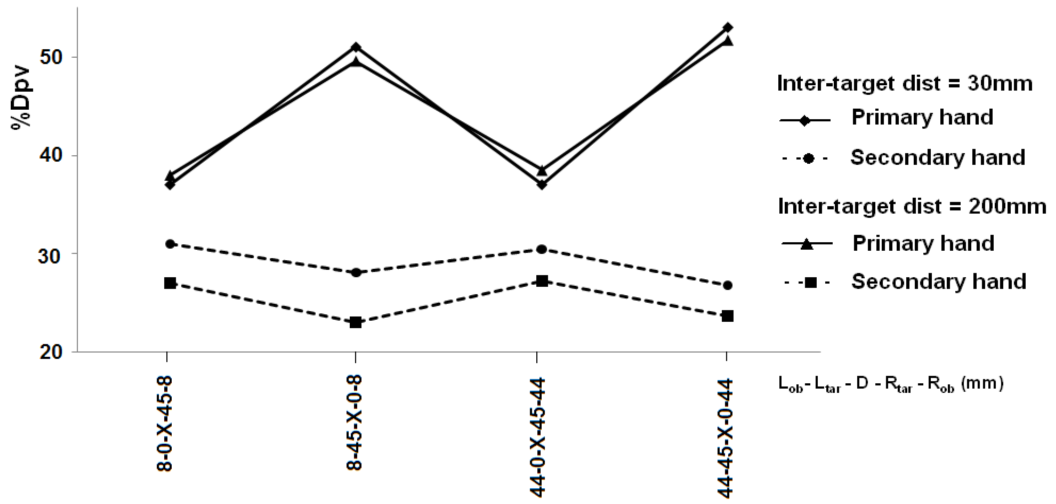


Fig. 4.16: %Distances to target, moved by primary and secondary hands in each task condition

Distance-at-gaze shift (Dgs)

The distance traveled by the secondary hand up to the instant when a shift in gaze occurs from the primary to secondary target in these target-asymmetric bimanual trials in which terminal gaze strategy was used, was computed.

Table 4.4: Mean DFRs of different subjects, classified according to trial condition

	Obj size (mm)	D (mm)	Sec Hand	DFR Sub1	DFR Sub2	DFR Sub3	DFR Sub4	DFR Sub5	DFR Sub6
8-0-30-45-8	8	30	R	0.84	0.83	0.85	0.79	0.84	0.8
8-0-200-45-8	8	200	R	0.75	0.79	0.74	0.67	0.77	0.73
44-0-30-45-44	44	30	R	0.82	0.84	0.84	0.8	0.86	0.85
44-0-200-45-44	44	200	R	0.74	0.7	0.77	0.73	0.79	0.73
8-45-30-0-8	8	30	L	0.55	0.59	0.52	0.52	0.6	0.53
8-45-200-0-8	8	200	L	0.49	0.51	0.48	0.45	0.48	0.48
44-45-30-0-44	44	30	L	0.52	0.56	0.53		0.57	0.5
44-45-200-0-44	44	200	L	0.5	0.49	0.5	0.45	0.5	0.47

Fig 4.17 shows the Dgs of the secondary hand across different subjects and trial conditions.

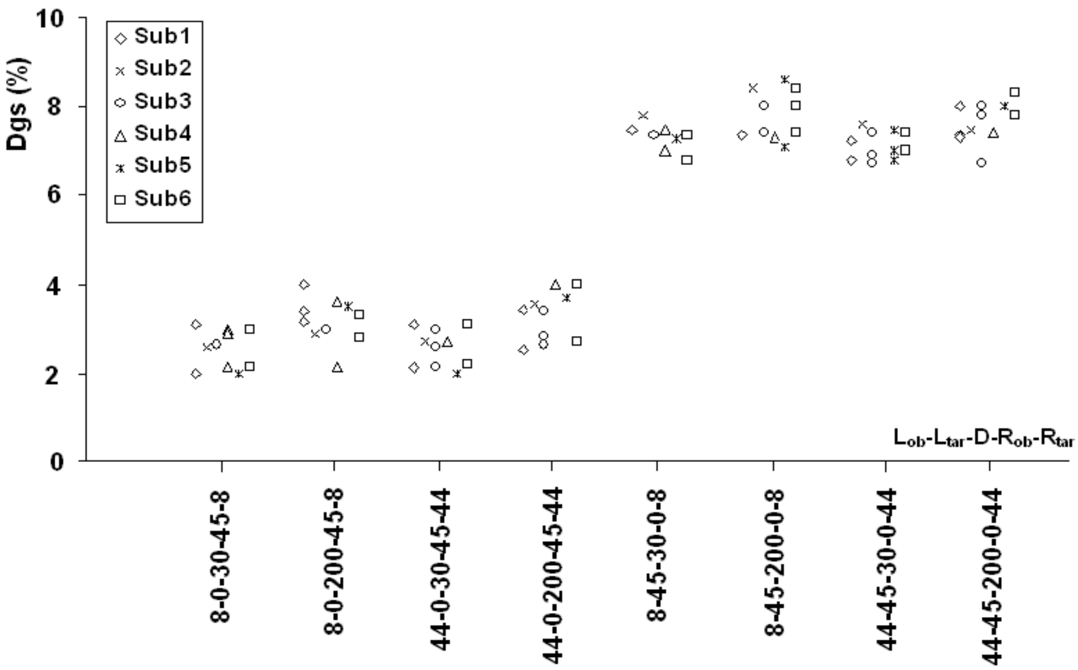


Fig. 4.17: Dgs of secondary hand of subjects in each task condition

From fig 4.17, it can be observed that although there is little difference in Dgs of secondary hand with change in object size or inter-target distance, the effect of target asymmetric coupling could be significant. When the left hand performs the primary zero-tolerance task, the corresponding Dgs was found to be significantly lesser than when the right hand performs the same primary zero-tolerance task in the different subjects (comparison of means between the two hands performing the primary task was significant with $P < 0.001$).

4.3.2.2. Predictive gaze strategy

In target-asymmetric bimanual trials in which the predictive gaze strategy was observed, the primary and secondary hand movements started simultaneously, similar to the other bimanual trials. However, the two hands did not reach peak velocity simultaneously. Irrespective of whether the left or the right hand performed the primary 45 mm-tolerance task, the secondary hand reached peak velocity at an average of 117±33 ms after the primary hand reached its peak velocity. At some point during the deceleration phase of the movements, a gaze shift occurs from the primary to the secondary target, following which both objects are placed on their respective targets. Target placement occurred first at the primary target, before the secondary hand zeroed in on its target. Fig 4.18 shows the typical velocity profiles of primary and secondary hand movements in a trial of type 8-0-30-45-8 of 1 subject.

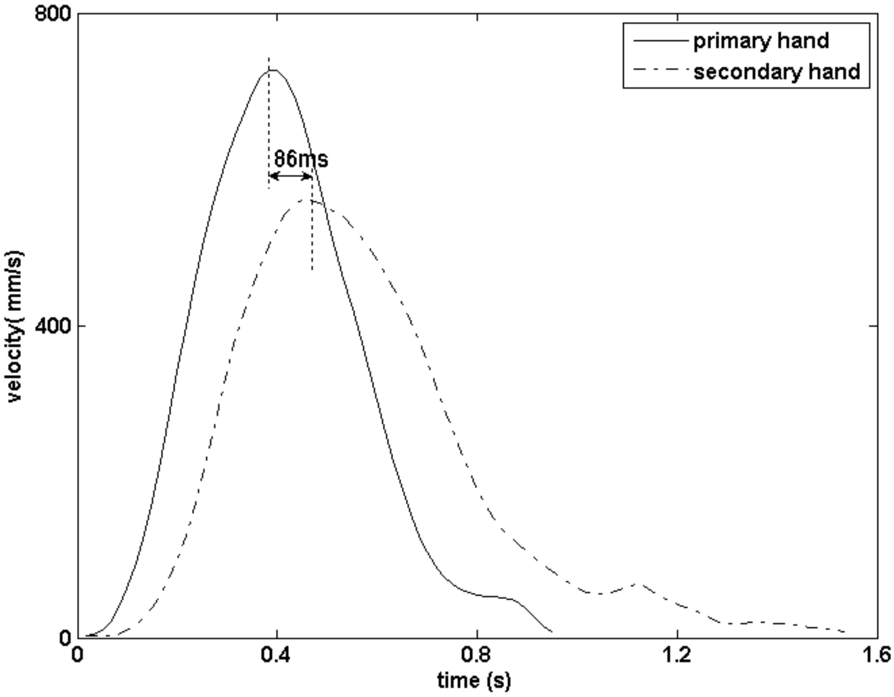


Fig 4.18: Typical velocity profiles of primary and secondary hands of 1 subject adopting predictive gaze strategy in an asymmetric bimanual trial

The primary hand movements to the 45 mm tolerance target were compared to their respective unimanual counterparts (right or left single-handed movements to 45 mm tolerance targets) in terms of total time of movement, time-to-peak velocity and Dpv. The time-to-peak velocities of the primary movements of all target-asymmetric bimanual trials in which predictive gaze strategy was used were similar (irrespective of task condition and whether the primary hand was the left hand or the right hand). Hence the average time-to-peak velocities of each subject, collapsed across the task conditions was compared with the average time-to-peak velocities of single-handed movements to similar 45 mm tolerance targets in fig 4.19.

Fig 4.19 shows that the primary hand's time-to-peak velocity is similar to the time taken by single-handed movements by the left/right hands to move to the same 45 mm tolerance target located at the same distance. The average time of deceleration (time from peak velocity to end of movement) of the primary movements was compared to their unimanual counterparts in fig 4.20.

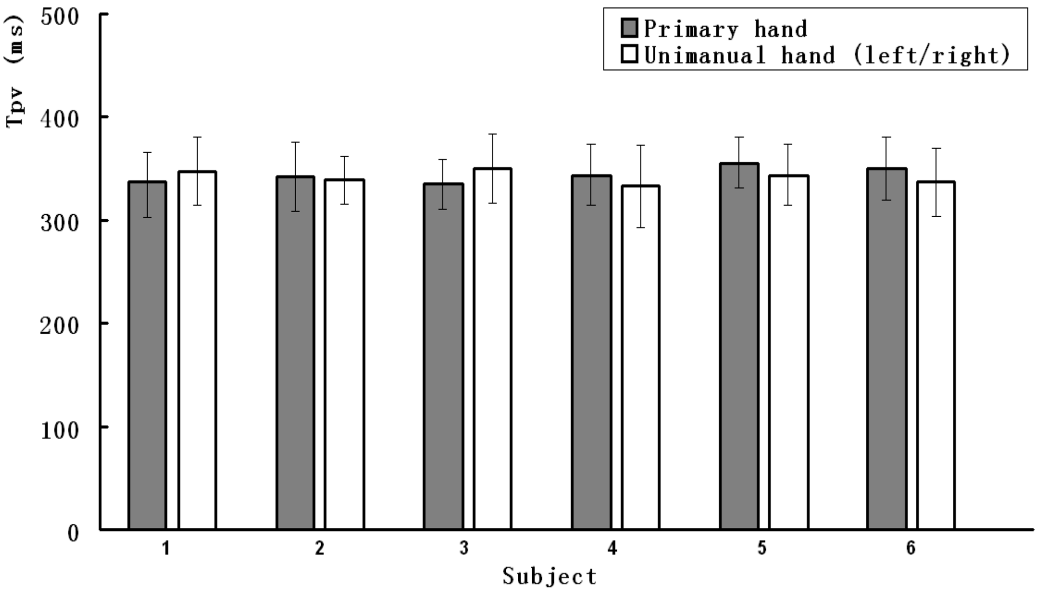


Fig. 4.19: Comparison of the time-to-peak velocity of the primary hand and the same hand in unimanual conditions

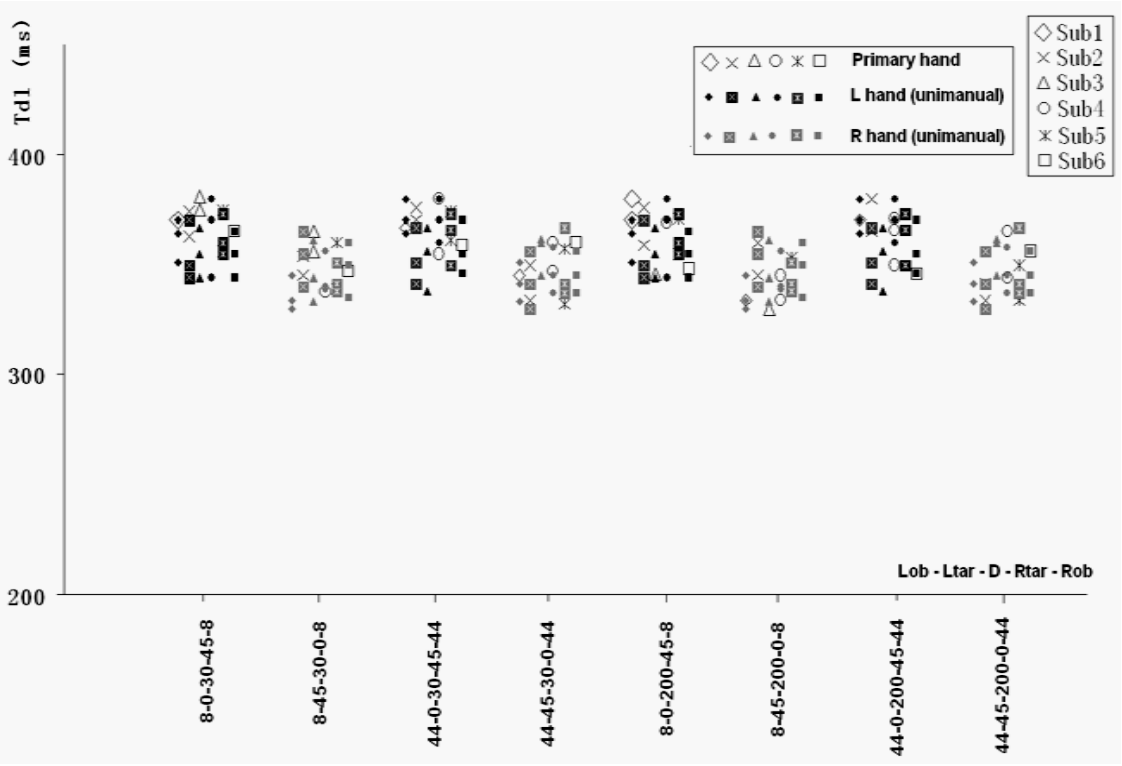


Fig. 4.20: Times of deceleration phase of primary hand movements (time from peak velocity to end of movement) and corresponding hand movements in unimanual conditions

Thus, the primary movements, irrespective of whether the left hand or the right hand performs the primary task, seem to take the same time to complete the place-movement as their corresponding single-handed movements. Fig 4.19 shows similar times for acceleration phases and fig 4.20 shows similar times for deceleration phases, implying that the time of each phase of the primary bimanual movement is similar to that of the corresponding unimanual movement of the same hand. A comparison of their means established that the difference between the means of acceleration phase times, deceleration phase times and total movement times of the primary movements and corresponding single-handed movements was not significant (***P*** >0.5). Similarly, a comparison of the primary Dpv means of the bimanual tasks and their unimanual counterparts also indicated that they were not significantly different (***P*** = 0.41). However, since the primary and secondary hand movements fell out of synchrony even during the acceleration phases of the movement, analyses of differences in end-times of the two movements, the secondary hand's Dpv and distance moved up to the instants of gaze shift etc were not performed for this strategy.

4.3.3. Asymmetry in object size and target tolerance

There were four main types of trials in this category:

1. 8-0-30-45-44
2. 8-0-200-45-44
3. 8-45-30-0-44
4. 8-45-200-0-44

Four more trial types were obtained by reversing both the object sizes and their relative target tolerances between the two hands, i.e.:

5. 44-0-30-45-8
6. 44-0-200-45-8
7. 44-45-30-0-8
8. 44-45-200-0-8

Thus, a total of 8 trial types, with 3 repetitions each, were performed by each of the 6 subjects in this category.

Both terminal and predictive gaze strategies were exhibited by subjects across the different trials. Terminal strategy was observed in 68% of the trials, and predictive strategy was exhibited in the remaining 32% of trials. Table 4.5 shows the distribution of terminal vs. predictive strategies across different trial conditions and subjects.

Adoption of the terminal or predictive strategies seems to be random, both within and between subjects. Neither the task conditions nor the individual subject strategies seemed to have any significant effect on which eye-hand coordination strategy was used in the trial (***P***>0.5).

Table 4.5: Distribution of terminal and predictive strategies across object & target-asymmetric trials

	Sub1			Sub2			Sub3			Sub4			Sub5			Sub6		
8-0-30-45-44	T	T	P	P	T	T	P	T	T	T	T	T	T	P	T	T	P	T
44-45-30-0-8	P	T	T	P	T	P	P	P	T	T	T	P	P	T	P	T	T	T
8-0-200-45-44	T	T	T	P	T	T	T	P	T	T	T	P	P	T	T	T	P	T
44-45-200-0-8	T	P	T	P	T	T	P	T	T	T	P	T	T	P	T	T	T	T
44-0-30-45-8	T	T	P	T	T	P	T	T	T	P	P	T	T	P	P	P	T	T
8-45-30-0-44	P	T	T	P	T	T	T	T	T	P	T	P	T	T	T	T	T	T
44-0-200-45-8	T	T	P	P	P	T	T	T	T	T	T	P	P	T	P	T	P	T
8-45-200-0-44	T	T	T	T	P	T	T	T	T	P	T	T	T	T	P	T	T	P

Since the choice of terminal or predictive strategies depended on the tolerance of the primary and secondary targets, subsequent analyses based on which gaze strategy is adopted in each trial is similar to the analyses in the target-asymmetry (but same object sizes) section of the results.

4.3.3.1. Terminal Gaze Strategy

Onset, time-to-peak velocity and end times of hand movements

In these bimanual trials, the two hand movements are initiated together and reach peak velocities simultaneously. The average difference in movement onset times between the left and right hands is 30±19 ms and the average difference in time-to-peak velocities of the two hands is 35±31 ms. It was also observed that neither the task conditions nor individual subject preferences significantly affected the order in which the left and right hands started the movements or reached peak velocity. In this terminal strategy, although both hand movements were initiated together and reached peak velocities together, movement to the zero-tolerance target would take precedence in execution during the deceleration phase of the movement, followed by movement to the higher tolerance target, irrespective of object size or which hand was performing the zero-tolerance task. The placements of the two objects at their respective target positions were thus never simultaneous. The difference in end times of the primary and secondary hand movements, both within and between subjects for each trial condition, is shown in fig 4.21.

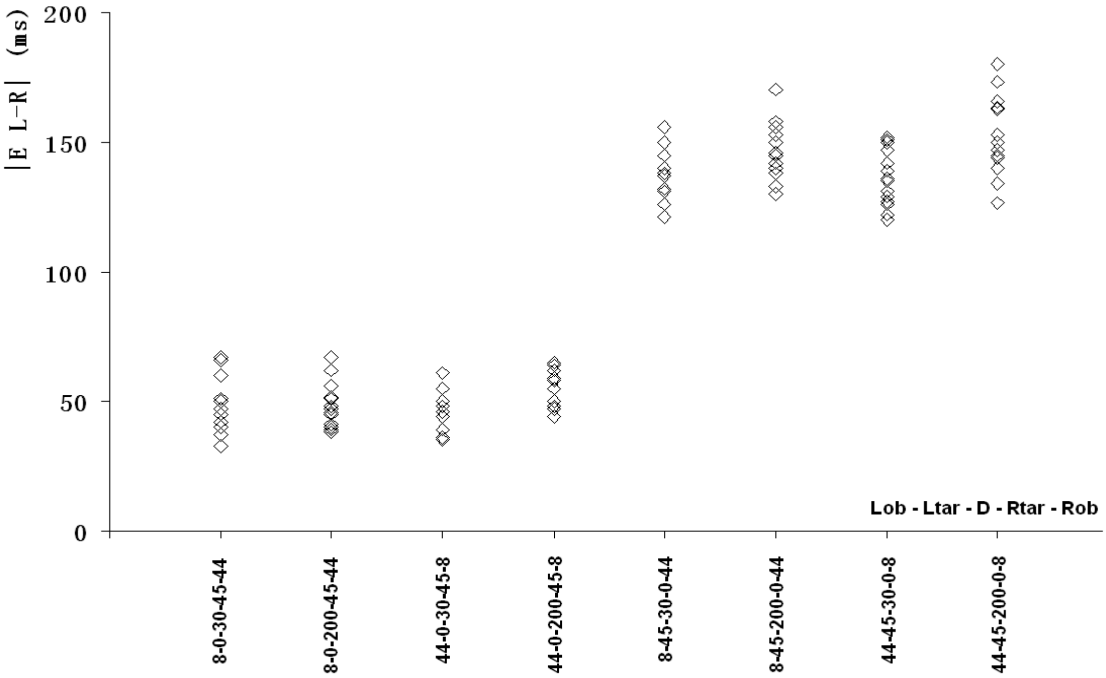


Fig. 4.21: Difference in end-times of primary and secondary movements in each bimanual condition

Although the end times between the two hand placements did not vary significantly with asymmetry in object size or target tolerance or the differences in inter-target distance (***P***>0.5), it increased when the primary task is performed by the right hand and the secondary task is performed by the left hand, as against the left hand performing the primary zero-tolerance task. The average difference in end times between the primary and secondary hands when the right hand performs the primary task is significantly higher than the average difference in end-times between the two hands when the left hand performs the primary task (***P***<0.001).

Fig 4.22 shows that although there is a difference in the primary movement times of the right and left hands, the left hand performing the secondary task has much longer deceleration times than the right hand performing the same secondary task, thus making the total movement time of a bimanual task longer when the right hand is the primary hand and the left hand is the secondary hand, as against the left hand being the primary hand and the right hand being the secondary hand. The object or target size asymmetry and inter-target distances within each hand-configuration (left-primary, right-secondary or right-primary, left-secondary) do not affect the times of the deceleration phases much.

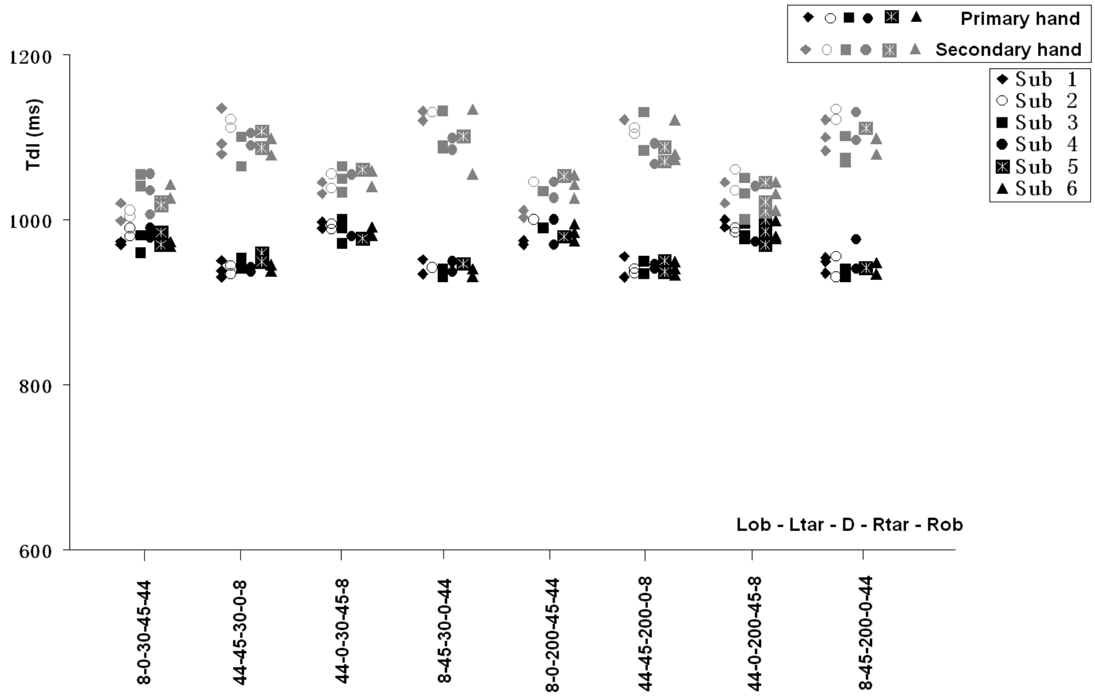


Fig. 4.22: Times of deceleration phase of primary and secondary hand movements (time from peak velocity to end of movement) in each bimanual condition

Similarly, the percentage distances at peak velocity (Dpv) of the primary hand did not vary significantly with task condition within each primary-secondary hand configuration. However, the distances moved by the primary hand was different depending on whether the primary hand was the left hand or the right hand (fig 4.23). The right hand as the primary hand moved more distance to target up to peak velocity than the left hand.

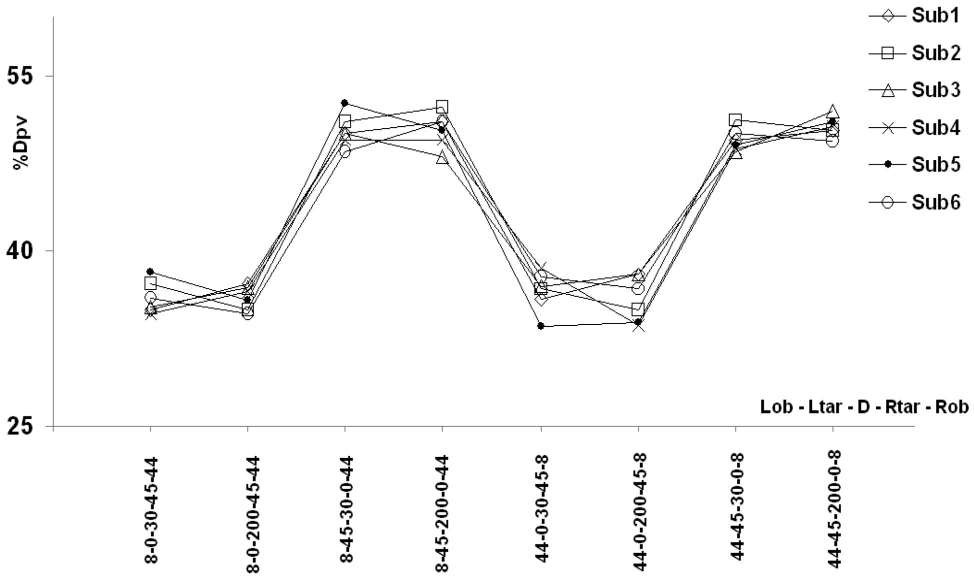


Fig. 4.23: %Distances to target, moved by primary hand up to instant of peak velocity in each task condition

Fig 4.24 shows the Dpv of the primary and secondary hand movements of one subject when the primary target was the zero-tolerance target. Within each hand, the secondary hand's Dpv is relatively constant with the asymmetry in object size, but decreases with increasing inter-target distance. When comparing the right and left hands performing as secondary hands, the left hand's Dpvs are further reduced than the right hand's Dpvs for similar task conditions. The mean DFRs of the secondary hand, classified according to object size, inter-target distance and hand are presented in table 4.6. Thus, irrespective of whether the right hand is the primary hand or the secondary hand, its Dpv is always higher than that of the left hand in similar trial conditions.

Table 4.6: Mean DFRs of different subjects, classified according to trial condition

	DFR Sub1	DFR Sub2	DFR Sub3	DFR Sub4	DFR Sub5	DFR Sub6
8-0-30-45-44	0.84	0.83	0.85	0.79	0.84	0.8
8-0-200-45-44	0.75	0.79	0.74	0.67	0.77	0.73
44-0-30-45-8	0.82	0.84	0.84	0.8	0.86	0.85
44-0-200-45-8	0.74	0.7	0.77	0.73	0.79	0.73
8-45-30-0-44	0.55	0.59	0.52	0.52	0.6	0.53
8-45-200-0-44	0.49	0.51	0.48	0.45	0.48	0.48
44-45-30-0-8	0.52	0.56	0.53		0.57	0.5
44-45-200-0-8	0.5	0.49	0.5	0.45	0.5	0.47

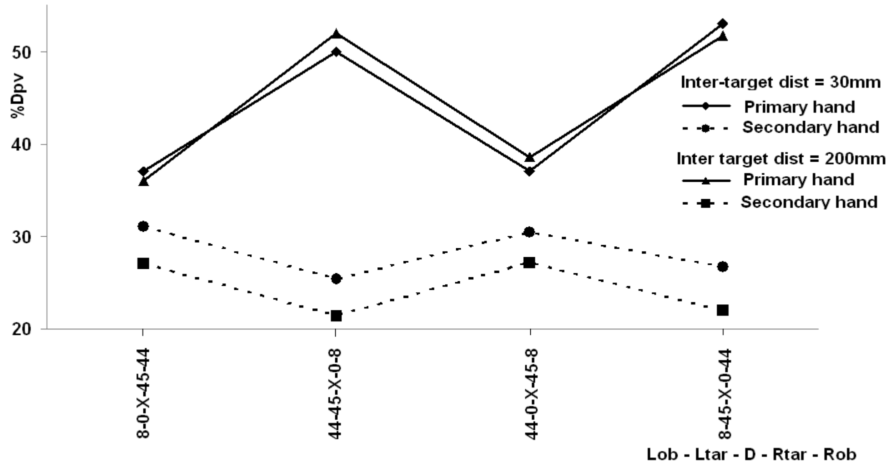


Fig. 4.24: %Distances to target, moved by primary and secondary hands during different bimanual trials conditions

Distance-at-gaze shift (Dgs)

Fig 4.25 shows the Dgs of the secondary hand across different subjects and trial conditions. Fig 4.25 shows that although there is no significant difference in Dgs of secondary hand with asymmetry in object size or change in inter-target distance, the effect of target asymmetric coupling is significant – i.e., when the left hand performs the primary zero-tolerance task, the corresponding Dgs is significantly lesser than when the right hand performs the same primary zero-tolerance task in the different subjects (comparison of means between the two hands performing the primary task is significant with $P < 0.001$).

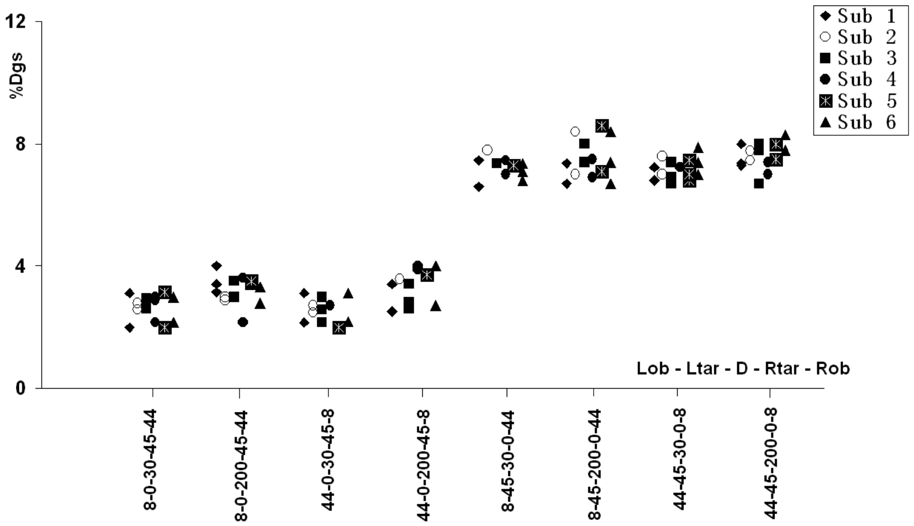


Fig. 4.25: %Distance to target, traveled by secondary hand up to instant of gaze shift

4.3.3.2. Predictive gaze strategy

In these bimanual trials in which the predictive strategy was used, the primary and secondary hand movements started simultaneously, similar to the other bimanual trials. However, the two hands did not reach peak velocity simultaneously. Irrespective of whether the left or the right hand performed the primary 45 mm tolerance task, the secondary hand reached peak velocity at an average of 122±27 ms after the primary hand reached its peak velocity. At some point during the deceleration phase of the movements, a gaze shift occurs from the primary to the secondary target, following which both objects are placed on their respective targets. Target placement occurred first at the primary target, before the secondary hand zeroed in on its target. Similar to the target-asymmetry trials in which the object sizes for the two hands was the same, the primary movement in these trials was comparable to their corresponding unimanual counterparts to 45 mm targets in terms of time-to-peak velocity, time of deceleration, and %distances up to peak velocity.

Thus, these trials were similar to those bimanual trials in which object sizes were the same between the two hands but the target tolerances were asymmetric. Object asymmetry seems to have had little effect on movement kinematics, and both the temporal and spatial characteristics of movements were similar to the target-asymmetry category of bimanual trials. The results in each category corresponded to similar results when only the target tolerance was varied between the two hand tasks.

4.4. Discussion

4.4.1. Object-asymmetry

When object size is asymmetric and target tolerance is symmetric between the two hands, the two hand movements are initiated simultaneously and reach peak velocities together. The difference in the end-times of movements increases significantly with decrease in target tolerance and increase in inter-target distance. Although there is no systematic difference as to which hand is chosen to lead at the time of movement onset or at peak velocity, there is clear left hand precedence in the terminal phases of those movements that don't end simultaneously. Whether the two hand movements terminate sequentially or synchronously, there is a systematic preference for the left-hand being chosen as the primary hand (primary task defined by the target which is foveated first, and subsequently as that target at which object-placement occurs first). These temporal characteristics are unaffected by the asymmetry in object coupling between the two hands. A strong predominance of left hand/ non-preferred hand selection as the primary hand suggests that visual guidance of the left hand is considered critical to initiate the movement of both hands. The left/non-preferred hand may be at a guidance disadvantage in absence of spatial visual reference, while control of the right/ preferred hand might rely more on proprioceptive/peripheral visual information.

Analysis of the gaze patterns indicates that the use of the terminal and predictive strategies depends on target tolerance (0mm target tolerance => terminal strategy, 45 mm target tolerance => predictive gaze strategy). The selective gaze pattern in which only the primary target is foveated and movements to both targets are completed simultaneously is observed in the symmetric bimanual trials, but is not observed in similar task conditions when the asymmetry in object size was introduced. One hypothesis for the absence of this gaze strategy in asymmetric trials is that exhibition of the selective gaze strategy is a highly learned behavior and since introduction of an asymmetry in the task makes it harder to learn, subjects may have not yet learnt such a highly coordinated pattern of movement. This hypothesis is in accordance with Amazeen et al.'s (2005) observation that asymmetric bimanual movements are more difficult to perform than symmetric movements and may require a greater amount of attention. Similarly, the intermittent gaze strategy in which subjects make multiple gaze transitions between the two targets is also absent in object-asymmetric trials.

In terms of the spatial aspects of coordination, the primary hand moves almost the same distance to target at the time of peak velocity in all trials, irrespective of task conditions, just as in the symmetric bimanual trials. The secondary hand Dpv are scaled to the primary hand's Dpv, with the distance fraction ratio varying significantly with both target tolerance and inter-target distance. Again, these spatial aspects are unaffected by the asymmetry in object sizes between the two hands. In trials in which the predictive gaze strategy was used, both the primary and secondary hands had moved equal distances to target at the time of gaze shift, similar to the symmetric bimanual trials. In those trials in which the terminal gaze strategy was used, the distance moved by the secondary hand to its target at the time of gaze shift decreased with increasing inter-target distance.

Except for the effects of intermittent gaze strategy in symmetric bimanual trials, the results from the object-asymmetric bimanual trials are almost identical to their symmetric bimanual trial counterparts. Thus, although object asymmetry may have increased the difficulty of the bimanual task as a whole (because of which the intermittent and selective gaze strategies may be absent in these trials), it seems to have little effect on the subject's perception of "asymmetry" - kinematics of both hand movements are coupled in ways similar to those in tasks with comparable symmetric bimanual task constraints.

4.4.2. Target-asymmetry

In target-asymmetric bimanual trials, either a terminal gaze strategy in which subjects chose to complete the zero-tolerance task first, or a predictive strategy in which subjects chose to complete the 45mm-tolerance task first were observed across the different trial conditions. Since both these strategies were used for ~50% of all the trials, choice of one strategy over another could not be attributed to any specific task condition or hand-asymmetry effects. Both these patterns of behavior were exhibited during the practice trials also, and hence it was difficult to identify if one was more advantageous or preferred over the other.

A key difference between the target-asymmetric trials and symmetric/object-asymmetric bimanual trials is that there was no systematic left hand preference for performing the primary movement in these trials. Subjects chose either hand for the primary movement, and the movement kinematics depended on what gaze strategy was used to complete the task. The difference between the nature of coupling of the two hand movements thus depended on which gaze strategy was adopted for performance of the task, and hence movement characteristics are described as a function of gaze strategy in the subsequent sections.

Terminal strategy

Both primary and secondary hand movements were initiated together, and reached their respective peak velocities simultaneously. During the deceleration phase of the movements, the hand performing the easier task slowed down faster than the other hand, such that the zero-tolerance task was completed first, after which a gaze shift to the secondary target enabled secondary hand movement completion. The difference in end-times between the two hands did not vary significantly with difference in object size or inter-target distance. However, there was a significant difference in the delta-end times depending on which hand performed the primary movement. The difference in end-times between the two hand movements was much higher in trials in which the right hand was the primary hand, than in those in which the left hand performed the primary zero-tolerance task. To determine if this difference in end times was due to a difference in the primary hand movement times between trials, or only due to differences in the secondary hand movements, the absolute movement times of the primary and secondary hands in different trial conditions were analyzed.

Earlier studies by Roy (1983) and Sainburg et al. (2000) have shown that left hand reach movements have longer deceleration phases than similar right hand reach movements in right-handed subjects making unimanual reach movements to precise targets. In accordance with these earlier observations, in the terminal strategy trials with target-asymmetry in our experiment, the left hand had longer deceleration times than the right hand when each was used as the primary hand in similar task conditions (Tdl times). However, beyond the differences in primary movement times, the total movement time in a bimanual task was less when the left hand was the primary hand and the right hand was the secondary hand, than vice versa. This was because the left hand performing as the secondary hand slowed down much more with respect to the right hand, than the right hand did, with respect to the left hand. Thus there seemed to be an advantage in terms of movement time in performing a bimanual task such that the left hand task was completed first, and the right hand task execution was secondary in priority.

Dpv of the primary hand varied significantly depending on which hand was the primary hand. The right and left hands performing as primary hands in the bimanual tasks had moved similar distances to target at the instant of peak velocity as in their respective unimanual trials. This comparison between the primary movement and the corresponding unimanual movement indicates that the primary hand movement in a bimanual task is probably uncompromised by the additional secondary task to perform.

Indeed, the secondary movement is scaled down, depending on the primary and secondary task difficulties and the inter-target distance. This is evident from the observation that in symmetric bimanual trials, when both target tolerances were 45 mm, the secondary task was not scaled down with respect to the primary Dpv, and DFR was ~1. However, in target asymmetric trials in which the primary task is a zero-tolerance task, the same 45mm-tolerance secondary task is scaled down even at peak velocities, with DFR ~ 0.7-0.8 with respect to the primary task.

Furthermore, DFR in target-asymmetric trials vary significantly depending on the hand. The secondary Dpv, when the left hand is the secondary hand is smaller than the secondary Dpv when the right hand is the secondary hand. So although the right hand’s primary Dpv is much higher, the secondary hand slows down much more with respect to the primary hand when the left hand is the secondary hand.

This difference in performance between the left and right hands, whether as the primary or the secondary hand, could be either due to a difference in their feedback processing capability (Flowers 1975) or due to an innate difference in the efficiencies with which the two hand movements can be programmed/executed, arising from differences in the levels of usage of each hand over a lifetime (Elliot et al. 1995). However, irrespective of what causes this difference, the systematic choice of the left hand as the primary hand in symmetric trials seems to indicate a strategic choice in minimizing the total movement completion time by maximizing the efficiency with which the available feedback resources can be utilized. That is, because the dominant (right) hand is more effective as a secondary hand (smaller performance decrement) than the left hand, it is optimal to make the left hand primary.

Predictive strategy

In the predictive strategy trials, the two hand movements were initiated together but not synchronized at peak velocity. The hand moving to the secondary target accelerated more slowly to reach a lower peak velocity (with respect to the primary movement) and at a later point of time. This strategy is very different from the coordination patterns observed so far (symmetric tasks, object-asymmetric tasks and target-asymmetric tasks in which terminal strategy was used), in which temporal synchrony was maintained until peak velocity, regardless of task conditions.

The total movement time in bimanual tasks in which this coordination strategy was adopted was greater than the same corresponding tasks in which the terminal strategy was adopted. This raises the question as to whether the predictive strategy is just an intermediate step in learning to use the most optimal strategy, and that with enough practice subjects would have consistently adopted only the terminal strategy in asymmetric bimanual trials or whether the predictive strategy represents an attempt to optimize something other than the movement time. The latter hypothesis is possible because time was not a constraint strictly imposed on any of these movements.

Hence, in order to test what this specific form of predictive strategy means in terms of asymmetric bimanual movements, we may need to design experiments in future where we impose a strict constraint on movement time (or make speed a priority) and observe if the terminal or the predictive strategies are consistently preferred over the other.

4.4.3. Conclusion

Introducing asymmetry in bimanual tasks has aided in our understanding of the effects of task constraints on movement coupling: The secondary hand’s DFR is affected as a function of the primary task difficulty and the inter-target distance.

Object-asymmetry does not seem to change a subject’s behavior as much as asymmetry in target tolerance. Bimanual trials in which the task conditions were reversed between the two hands indicate that there may be an overall advantage in movement time when the left hand performs the primary task and the right hand performs the secondary task than vice versa. Hence, in symmetric bimanual trials in which both task difficulties are identical, the left hand may be systematically preferred as the primary hand due to the inherent asymmetries in the feedback processing capabilities of both hand systems.

CHAPTER 5

MODEL

5.1. Introduction

Modeling is an important experimental and analytical tool that improves understanding of the fundamental processes underlying observations by requiring an explicit formulation of the problem in terms of inputs, assumptions, and goals. Mathematical models of human activities typically simulate patterns of behavior that help us to extend our understanding of phenomena beyond the range of empirical data collected, and thus test both the limits of our hypotheses and the system being modeled.

Models help us to formalize the principles of empirical sciences such that they can be applied in a broader context, to solve problems different from those that prompted the initial model development. In this process, individual principles developed from isolated empirical studies are combined and are continually refined to gradually become a general theoretical framework for understanding several associated phenomena.

In the area of motor control, several models of reaching have been proposed. From all these models, some common principles of how the CNS generates movements have emerged: Once the CNS selects the targets or goals to reach, it must eventually compute a motor plan and generate the coordinated forces needed to achieve the goal. Such a plan could be computed in advance, before movement initiation, or the computation could evolve during the course of the movement. A motor plan computed in advance is referred to as a *motor program* - a set of motor commands defining the essential details of the movement that is composed in advance of the motion at the executive level (Shadmehr and Wise 2005). Although the motor program reflects an acquired motor skill, unanticipated disturbances from the environment will affect the execution of the movement, or noise in the planning/execution networks might necessitate adjustments to the motor program during the course of the movement execution. A motor control system in which the motor program is modified based on feedback of the consequences of the movement is generally referred to as a closed-loop system.

Feedback in a closed-loop model of movements is mainly of two types, intrinsic and extrinsic. Intrinsic feedback refers mainly to proprioceptive and visual feedbacks that arise as direct consequences of the movement. On the other hand, extrinsic feedback refers to indirect and motivational feedback about the outcome of the movement, such as knowledge of results and knowledge of performance. In the absence of extrinsic feedback, learning still occurs because the person that makes the movement has been involved in error perception and subsequent correction. However, augmenting the intrinsic feedback with information about the performance outcome helps in integrating the input and the corresponding movement outcome into long-term memory. Fig 5.1 illustrates a basic closed-loop system with feedback control.

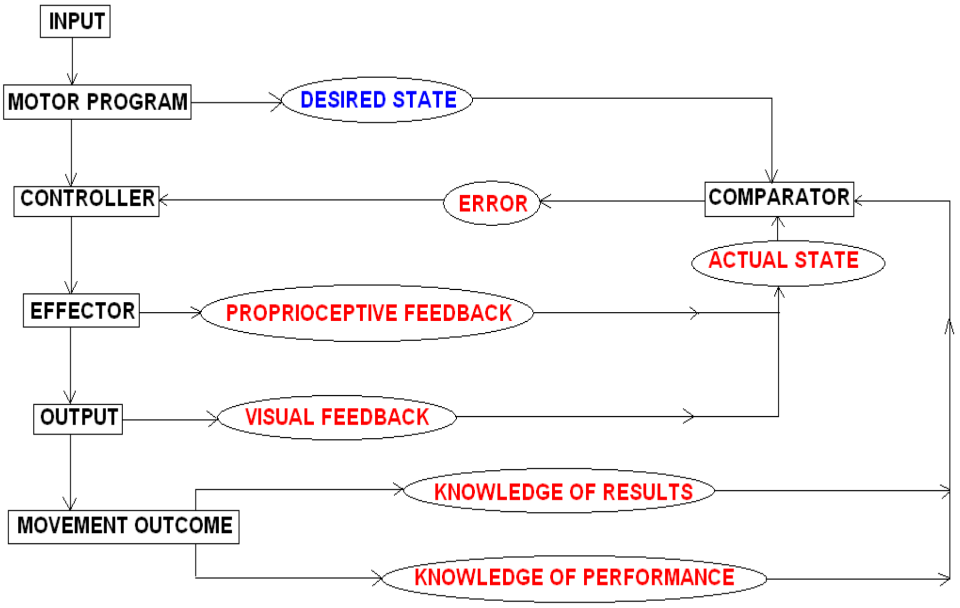


Fig. 5.1: Closed-loop system of feedback control

At a neural organizational level, the organization of an action is said to consist of two stages: assembling an action and guiding the action to completion. Referred to as coordination and control respectively (Kugler, Kelso and Turvey, 1980), two levels of explanation have traditionally been used to understand these processes - psychological and physiological. At the psychological or intentional level, coordination refers to formulating the rules of action intended to achieve a goal state. The control of the action is about applying these rules on the occurrent environment specified by perceptual information. On the physiological level, coordination can be described as the alignment of the action system with respect to the efferent neural signals that appropriately potentiate the necessary effectors, and control is defined as the afferent tuning of the effector system.

This understanding has led to the evolution of two main approaches to movement modeling over the years: an information processing approach and a dynamic systems approach. The dynamic systems approach has sought to understand functional synergies that underlie coordination by looking for equations of constraints in physical principles. The goal has been to understand the action system organization in terms of dynamical constraints and principles of self-organization at many levels. Some of the examples of such modeling have been various types of optimization, such as minimum torque change (Uno et al. 1989), minimum energy (Alexander 1997), equilibrium point hypothesis (Shadmehr 1998) etc. This approach to modeling typically requires a structural model of the underlying system dynamics - for e.g., multi-limb models of the hand, with different degrees of freedom at each joint interacting with one another. There are also kinematic models of motor control like the minimum jerk model (Flash and Hogan 1985), or the minimum variance model (Harris and Wolpert 1998), both of which are elegant models that predict smooth movement trajectories and bell-shaped velocity profiles using minimization of the jerk or end-point variance cost function. Although these models produce dynamics/kinematics that are very close to the observed characteristics of experimental movement data, they do not account for feedback-based corrections during the course of the movement. These models do not account for online control of movement parameters after movement initiation (when the execution of a motor plan begins), and reflect characteristics of an open-loop motor control system.

The focus of the information processing approach to modeling is the emphasis on the role of perceptual information from the environment in the form of multiple modes of feedback control laws governing their propagation (with associated sensor noise and delay parameters), and finally integrating motor commands with their respective sensory consequences, to derive optimal control policies. These descriptions of how a system would interact with the environment and gradually learn or acquire a motor skill could be overlaid on any dynamic system, as the system-dynamics themselves would form an internal dynamics loop in this broader framework of control. A computational approach to such a control-theoretic model of movements combines known theoretical precepts with empirical findings governing certain movement characteristics, enabling the simulation of non-deterministic and novel patterns of behavior, leading to better understanding of motor behavior and the organizing principles of coordination control and motor learning.

The computational study of motor control is fundamentally concerned with the relationship between sensory signals and motor commands. It seems unlikely that the CNS maintains a complete desired set of possible movement trajectories to each goal, in order to be able to compare every actual state with a desired state. Thus, at every step in the movement, the CNS may evaluate the goal in relation to the limb's current state, and then generate the desired change in state in real time, acting as a next-state planner. However, a closed-loop control approach, which relies on feedback of the errors in execution (difference between the desired and the sensory outcome of a movement), must contend with the substantial delay in propagation of the sensory consequences of a motor command to the CNS for subsequent analysis and error-correction. The delay in feedback propagation times suggests that the CNS may not have timely information about the current state of the limb from purely feedback sources (Kawato 1999, Wolpert et al. 2000). One possible solution to this problem is that although the CNS is not required to represent the motor-sensory transformations as they occur in the physical world, it may internally represent this transformation in order to be able to predict the consequences of a movement, thus leading to the idea of 'internal estimation models'. The notion of an internal model, a system that can mimic the behavior of a natural process, has emerged as an important concept in motor control. Two main types of internal models have been proposed:

(i) Forward models, which mimic the causal flow of a process by predicting the next state, given the current state and motor command, and

(ii) Inverse models, which predict the motor command that caused a particular state transition

Forward models have been shown to very useful to solve some fundamental problems in motor control:

- The delays in sensorimotor loops in the body are so large (as much as 200 ms for visual feedback of position) that feedback control of rapid movements is nearly impossible. With the use of a forward model for internal feedback, the outcome of an action can be predicted and acted upon, before sensory feedback becomes available.
- Forward models can also be used to transform errors between the desired and actual sensory outcomes of a movement into corresponding errors in motor program, thus being a useful input for motor learning.
- Finally, a forward model can be used for state estimation in which the model's prediction of a next state is combined with afferent sensory correction.

A basic internal model for estimating the next state, given the current state, is illustrated in Fig 5.2. The upper part uses the motor command and the current state estimate to achieve a next state estimate using the forward model to simulate the arm-dynamics. The bottom part uses the difference between the expected and actual sensory feedback to correct the forward model state estimate. The relative weighing of these two processes is mediated by the Kalman gain (Wolpert et al. 2000).

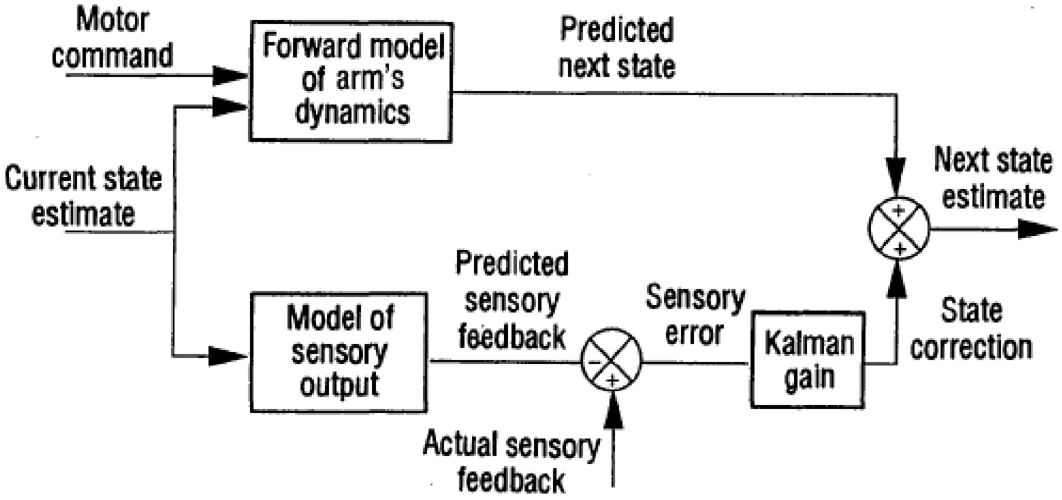


Fig. 5.2: An internal model to estimate the next state, given current state estimate (Miall and Wolpert, 1996)

Current modeling approach

The current modeling approach addresses the problem of bimanual coordination through a control theoretic approach similar to Wolpert et al. 1998. The two hands are modeled as point masses moving in 1-dimension, with the focus not being on the hand dynamic system but on how a limited resource model of feedback (vision/proprioception) could lead to the observed kinematics of the two hands. While the joint rotations that would be needed to take an end-effector to a target location are not explicitly modeled, the decisions about when and how the end-effector itself should be moved, in order to satisfy the dual task constraints (bimanual task), within the limits of the available feedback resources is modeled in terms of wrist velocity profiles. Visual feedback is decomposed into foveal and peripheral feedback, and a context-specific integration of proprioceptive and visual feedback is proposed, taking into account the noise in their respective sensors as well as movement experience.

5.2. Summary of empirical observations

A summary of the findings from the lab study is presented to document the specific behaviors that a model of bimanual coordination should be able to produce. In unimanual left and right handed movements to similar targets (same object size and target tolerance), both left and right hands take the same time to reach peak velocity. On average, the left hand moved significantly lesser distances to target than the right hand during the acceleration phase of the movements (from movement onset up to instant of peak velocity). The left hand movements also showed longer deceleration times than the corresponding right hand movements while moving to similar targets, which indicated that movement to a target took longer for the left hand than the right hand. Although deceleration times increased with increase in task precision for both the left and the right hands, task precision did not affect the time to peak velocity or the distance moved until the time to peak velocity for both the left and right hands (i.e. task precision did not affect the acceleration phases of single-handed movements as long as the distance-to-target remained constant).

In symmetric bimanual tasks, movements of left and right hands were always initiated together, irrespective of task condition, and they also attained their respective peak velocities simultaneously. However, although symmetric until peak velocity, the extent of synchrony during the terminal phases of the movements was significantly influenced by task parameters. The difference in movement termination times between the left and right hands increased significantly with decrease in target tolerance and increase in inter-target distance.

Four distinct eye-hand coordination patterns were identified, based on sequencing of hand movements and timing of gaze-shifts from one target to another. Known as the terminal, predictive, selective and intermittent strategies, these patterns were significantly dependent on inter-target distance and individual accuracy requirements of each hand task. The terminal gaze strategy in which the secondary target was fixated after completing the hand movement to the primary target, was observed in movements to targets of high precision (low tolerance), irrespective of object size and inter-target distance. The predictive gaze strategy in which the secondary target was fixated even before movement to the primary target was completed, was observed in movements to targets of low precision (high tolerance), irrespective of object size and inter-target distance. The terminal gaze strategy implied that although both movements were initiated together, the termination of the two hand movements were sequential, since the secondary hand completed movement to its target only after its target was fixated. The predictive gaze strategy also required the secondary target to be fixated before the secondary movement was completed, but target fixation occurred prior to primary movement completion, thus enabling the synchronous termination of both hand movements.

Although two other eye-hand coordination patterns - the intermittent and selective strategies were observed, the intermittent gaze strategy in which the subject made repeated gaze transitions between the primary and secondary targets was largely observed during the practice trials, before the other strategies emerged. Since this suggests that the intermittent gaze pattern may not be observed in well-learnt movements, and it is currently observed in a very small percentage of the experimental trials, this gaze behavior is not modeled explicitly. If the intermittent gaze behavior was excluded, then the effect of object size on differences in temporal symmetry of bimanual symmetric tasks becomes insignificant.

Similarly, the selective gaze strategy in which subjects complete movements to both targets while fixating their gaze only on one of them, seems to be the most evolved behavior and is once again observed in a very small percentage of all the trials – hence it is not modeled.

The left-hand target was predominantly the primary target and the right-hand target was the secondary target when the task conditions between the two hands were symmetric. When faced with competing visual demands, left hand guidance required more foveal visual information of the target, while right hand control could rely predominantly on proprioceptive/visual feedback, with the target in peripheral field of view, thus indicating an asymmetry in feedback requirements of the two hand systems when accuracy is critical. Although both the primary and secondary hands took the same time to reach peak velocity, the distance moved up to the instant of peak velocity varied between the two hands. Distances moved by the primary hand during the acceleration phase were similar to the left hand’s unimanual performance. However, the right hand performing the secondary task moved significantly lesser distances to target when compared to its unimanual performance during its acceleration phase. Its peak velocity was either the same as the left hand’s or smaller, depending on target tolerance and inter-target distance. The difference between the secondary hand's Dpv and the primary hand's Dpv increased significantly with decrease in target tolerance and increase in inter-target distance.

Temporal symmetry is only lost as a function of task difficulty during the terminal phases of bimanual movements. However, the distances traveled by the two hands during the acceleration phases of movements differ as a function of task difficulty and inter-target distance. This suggests that the asymmetric coupling is probably deliberately planned in advance (before movement initiation), to maintain temporal symmetry and fulfill the feedback requirements of each task. In terms of gaze strategy, both hands move the same distance to target during the initial phase in the predictive strategy and the secondary hand moves significantly smaller distance to target until peak velocity in the trials in which terminal gaze strategy is observed.

Although hand movements are spatially symmetric in the selective gaze strategy when the targets are close together (both within the foveal visual zone), and target tolerance is high, distances moved by both hands up to peak velocity in such bimanual tasks are similar to that of the corresponding single-handed left hand movements, and not the right handed movements.

Thus, these results seem to indicate that when the eyes are fixating one target, the movement to that target is the primary movement, and a primary movement is uncompromised with respect to its corresponding single-handed movement, i.e., the effect of adding a second task does not affect the primary movement. The secondary movement is pre-planned to compensate for the resource requirements of the primary task.

In symmetric bimanual tasks, both temporal and spatial aspects of symmetry were found to vary significantly with individual task difficulty and inter-target distance. However, since the effects of primary task difficulty on bimanual coordination could not be decoupled from the effects of secondary task difficulty in symmetric bimanual tasks, asymmetric bimanual tasks were also studied.

Asymmetry between the two tasks could be in object size, target tolerance or both object size and target tolerance. Asymmetry in object size did not significantly affect movements. Thus, in the trials with object asymmetry, subjects exhibited behavior similar to symmetric bimanual trials in terms of both eye-movements and spatio-temporal characteristics of hand movements.

However, when asymmetry was in target tolerance, one of the following two strategies was adopted in the movements:

1. *Terminal gaze strategy*

    Both hand movements are initiated together and reach peak velocities simultaneously, but the hand moving to the more difficult target (zero-tolerance) completes its movement first. The gaze shifts to the other target and the secondary movement is completed. This pattern of the more precise task being chosen as the primary task and the other one being the secondary task does not seem to be dependent upon whether the right hand or the left hand has to move to the more precise target. Difference in termination times increases with increase in inter-target distance and does not depend on object size. When the left hand performs as the primary hand, the difference in termination times between the two hands is smaller than when the right hand performs as the primary hand. Although the right hand takes less time to complete the primary movement than the left hand, the left hand performing as a secondary hand lags much more with respect to the primary right hand. This is evident from the distances traveled by each hand up to the instant of peak velocity. Thus, the total time of a bimanual movement is smaller when the left hand performs as the primary hand

2. *Predictive gaze strategy*

The two hand movements are initiated together, but they do not reach peak velocities simultaneously. The hand moving to the 45mm tolerance-target moves faster i.e., it reaches peak velocity earlier and also attains a higher magnitude of peak velocity compared to the secondary hand moving to the zero mm tolerance target. At some point in the course of its trajectory, gaze shifts from the primary to the secondary hand's target, after which termination of the secondary movement occurs.

5.3. Modeling

5.3.1. Behaviors for simulation

The following empirical results are the important behaviors that the model would simulate:

1. Unimanual tasks: Left and right hands movements show similar acceleration times for all task conditions and between the two hands also. But deceleration time varies, depending on both hand and task difficulty.
2. In bimanual movements, primary task is chosen as the movement to the target of higher difficulty (If target difficulties are symmetric, left hand's task chosen as the primary task).
3. Primary hand movement is uncompromised with respect to its corresponding unimanual movement in terms of both temporal and spatial aspects of movement kinematics.
4. Secondary hand movement is coupled to the primary hand movement such that temporal symmetry is preserved during the acceleration phases, but the peak velocity of the secondary hand is scaled down as a function of primary task difficulty and inter-target distance.

An example of (3) and (4) is that in those trials in which both target tolerances are 45 mm each, the secondary hand moves the same distance to target as the primary hand during the deceleration phases of the movement and both movements end at their target destinations simultaneously. However, when the two target tolerances are 45 mm and 0 mm each, and the primary movement is to the 0 mm-tolerance target, although the secondary movement is to the same 45 mm target just as in the previous case, the secondary hand's Dpv is ~ 0.7-0.85 times the primary hand's Dpv, and the two movements terminate sequentially. Even though the secondary movement is to the easier target, and it would have had much shorter deceleration time than a single-handed movement to the 0 mm target, in this bimanual configuration where it is chosen as the secondary task, it takes longer time to complete this task than the primary task to the 0 mm tolerance target. The secondary task's DFR also decreases with increase in inter-target distance. The bimanual trials in which both target tolerances are 0 mm, as the inter-target distance increases from 30 mm to 200 mm, DFR decreases significantly.

5. After the occurrence of peak velocity, online control of movements is based on feedback information from foveal visual, peripheral visual and proprioceptive sources.

5.3.2. Model description

Unconstrained point to point motions have been observed to be approximately straight with bell-shaped tangential velocity profiles. Theoretical analysis based solely on the movement kinematics and independent of the dynamics of the underlying musculoskeletal system have been successful when formulated in terms of the hand movement in extracorporeal space. The minimum jerk theory (Flash and Hogan, 1985) is one such model based on dynamic optimization theory, in which smoothness of a movement is quantified as a function of jerk (time derivative of acceleration). This model uses the methods of variational calculus and optimal control theory to find the trajectory that minimizes a certain criterion function (sum of squared jerk along the trajectory), subject to the dynamic constraints imposed by the system and the end-point constraints imposed by the specific movement.

For a particular one-dimensional trajectory x(t) that starts at time t=0 and ends at t_f, the jerk cost is defined as:

$$C = \frac{1}{2}\int_0^{t_f} \dddot{x}(t)^2\,dt \qquad \text{(eqn. 6.1)}$$

Generally for any function x(t) which is sufficiently differentiable in the interval $0 \le t \le t_f$, and for any performance index $L[t, x, \dot{x}, \ddot{x}, \ldots \frac{d^n x}{dt^n}]$ which is integrable over the same interval, the unconstrained cost function assumes an extremum when x(t) is the solution of Euler-Poisson equation:

$$\frac{\partial L}{\partial x} - \frac{d}{dt}\frac{\partial L}{\partial x} \ldots\ldots + (-1)^n \frac{d^n}{dt^n}\frac{\partial L}{\partial (x^n)} = 0 \qquad \text{(eqn 6.2)}$$

Since L= $\frac{1}{2}(\dddot{x})^2$, x(t) should be a solution to $\frac{d^3}{dt^3}\left(\frac{\partial \dddot{x}^2}{\partial \dddot{x}}\right) = 0$.The general solution to such a sixth order differential equation is the fifth order polynomial:

$$x(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^5 \qquad \text{(eqn 6.3)}$$

The constants a0, a1, a2, a3, a4 and a5 in the above equation can be determined using the boundary conditions at the onset and end of movement.

This minimum jerk model describes how a system should move from rest to a target location in desired time. However, it is like a feed-forward controller that describes the desired behavior of a system without taking movement feedback into account. To address this, Hoff and Arbib (1992) reformulated the solution to the functional such that the result was a feedback-control system. The system monitored both the location of the hand and the target at each instant of time, and ensured that each change in hand location always brought the hand in a mimimum jerk path to the target.

Fig 5.3 shows a one-handed control system that generates a smooth trajectory from an initial to a final location, in which the hand is modeled as a point mass and the movement is in 1 dimension. The hand is assumed to begin each movement at zero velocity and zero acceleration. States of displacement, velocity and acceleration are maintained throughout the movement. The goal of the movement is to reach and stop at a target located 400mm away. The duration of the movement is estimated as a function of the maximum acceptable jerk in the movement.

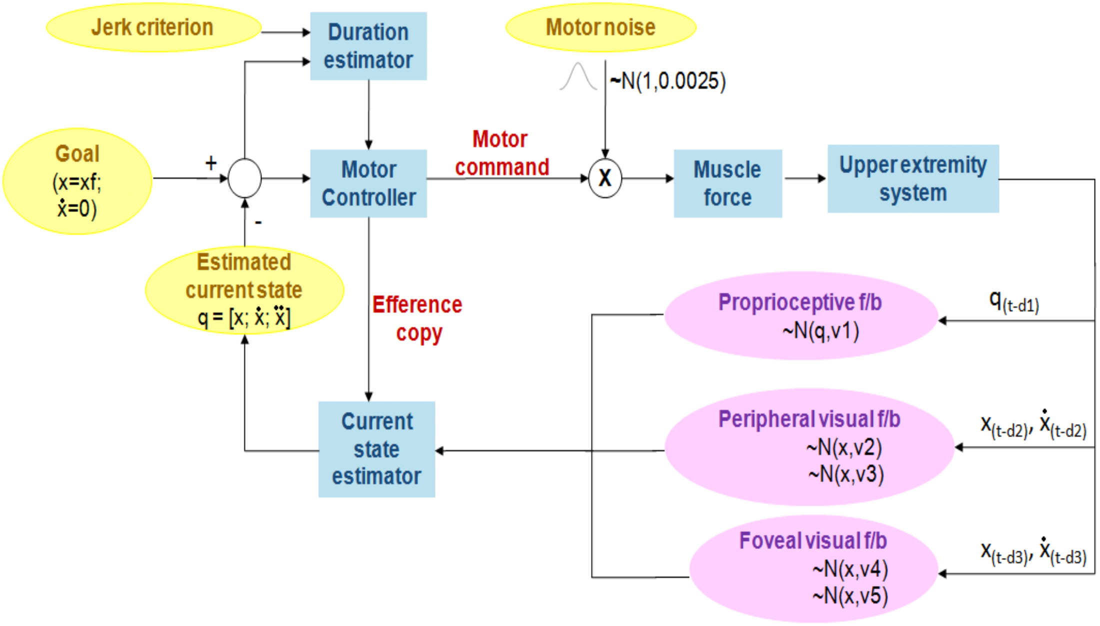
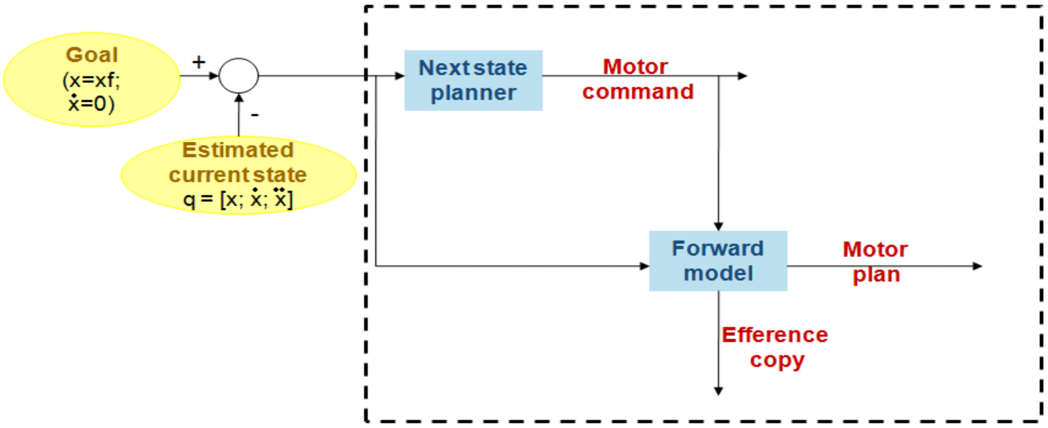


Fig 5.3: One-handed control system

Motor controller:



The controller consists of a next planner and an internal forward model. The next state planner was based on Hoff and Arbib (1992), with additions to handle multiple feedback channels with noise. The next state planner computes the next state, given the current state and the goal, using a minimum jerk criterion:

If q is the state of the system at any time t,

$$q = \begin{pmatrix} x \\ \dot{x} \\ \ddot{x} \end{pmatrix} \qquad \text{(eqn 6.4)}$$

If the movement is assumed to start at t_0 and end at t_f, D is defined as $D = t_f - t_0$,and τ represents normalized time (i.e. $\tau = \frac{t - t_0}{D}$), then the minimum jerk trajectory has the form:

$$x(t) = a_0 + a_1\tau + a_2\tau^2 + a_3\tau^3 + a_4\tau^4 + a_5\tau^5 \qquad \text{(eqn 6.5)}$$

Since $\frac{d\tau}{dt} = \frac{1}{D}$,

$$\dot{x}(t) = \frac{a_1}{D} + \frac{2a_2}{D}\tau + \frac{3a_3}{D}\tau^2 + \frac{4a_4}{D}\tau^3 + \frac{5a_5}{D}\tau^4\ ;$$

$$\ddot{x}(t) = \frac{2a_2}{D^2} + \frac{6a_3}{D^2}\tau + \frac{12a_4}{D^2}\tau^2 + \frac{20a_5}{D^2}\tau^3 \qquad \text{(eqns 6.6)}$$

The initial conditions are given by $x(t_0)=x_i$, $\dot{x}(t_0)=v_i$, $\ddot{x}(t_0)=p_i$.

At $t=t_0$, since $\tau=0$,

$$a_0 = x_i,\ a_1 = Dv_i,\ a_2 = \frac{Dp_i}{2} \qquad \text{(eqns 6.7)}$$

The endpoint conditions are defined as:

$$x(t_f) = x_f$$

$$\dot{x}(t_f) = 0$$

$$\ddot{x}(t_f) = 0 \qquad \text{(eqns 6.8)}$$

At t=t$_f$, since τ =1,

$$a_3 = \frac{-3D^2}{2} p_i - 6Dv_i + 10(x_f - x_i)$$

$$a_4 = \frac{3D^2}{2} p_i + 8Dv_i - 15(x_f - x_i)$$

$$a_5 = \frac{-D^2}{2} p_i - 3Dv_i + 6(x_f - x_i) \qquad \text{(eqns 6.9)}$$

Thus, we now have an expression for x(t), which is valid for any initial condition. For example, at any time into the movement t, if the initial state is given by q = [x$_i$ v$_i$ p$_i$]^T, the change in acceleration that should occur is given by:

$$\dddot{x}(t) = \frac{6a_3}{D^3} + \frac{24a_4}{D^3}\tau + \frac{60a_5}{D^3}\tau^2 \qquad \text{(eqn 6.10)}$$

At t = t$_0$, $\tau = 1; D = t_f - t$

Therefore,

$$\dddot{x}(t_0) = \frac{6a_3}{D^3} = \frac{60}{D^3}(x_f - x(t_0)) - \frac{36}{D^2}\dot{x}(t_0) - \frac{9}{D}\ddot{x}(t_0) \qquad \text{(eqn 6.11)}$$

If we write the control law as:

$$\dot{q} = Aq + Bx_f \qquad \text{(eqn 6.12)}$$

then the state transition equation is given by:

$$\dot{q}(t) = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -60/D^3 & -36/D^2 & -9/D \end{pmatrix} * q_{(t-1)} + \begin{pmatrix} 0 \\ 0 \\ 60/D^3 \end{pmatrix} * x_f \qquad \text{(eqn 6.13)}$$

where D is the duration of the movement; xf is the final target position and x_{ee} is the estimated position of the end-effector at any time t.

Since the above system needs a timekeeper (D is the time remaining to target), Hoff proposed a movement duration estimator as a cost function that took into account both jerk and time such that it estimated time remaining to target (D) as a function of the current state of the end effector, the distance to target x_t- x_{ee}, and a constant r that described the tradeoff between moving fast versus moving smoothly.

$$D = (60 * (xf - x_{ee}))^{1/3} * r^{1/6} \qquad \text{(eqn 6.14)}$$

where r is the weight on the tradeoff between the movement's smoothness and the duration of the movement to target.

The model iterates at small timesteps, typically 1 ms. At every step in the movement, the duration estimator recalculates the time of movement based on the current position of the hand and the maximum acceptable jerk in the movement (defined by the cost function r). The movement is ended when the hand reaches a certain 'target zone', defined by the target location and the associated tolerance in target location (target location ± target tolerance) and when the hand velocity has dropped to a value ≤ 5mm/sec. As the motor command is being fed to the muscle units, there is some execution noise in the system. Referred to as motor noise, this is assumed to be a Gaussian process with mean 1 and variance 0.0025 (mm/s^2) and is multiplied with the motor command signal.

Feedback about the movement performance is obtained from three sources: proprioceptive, peripheral visual and foveal visual. The delays in acquiring, propagating and processing these sources of information have been estimated by earlier studies to be ~ 30 ms, 50 ms and 100 ms respectively (Paillard 1996, Todorov et al. 2002, 2004, 2005). However, estimation of the consequences of the movement, as sensed by each source of feedback is also modeled as being noisy.

Feedbacks are modeled as stationary Gaussian processes with mean = actual value and constant variance (v_i). Foveal visual feedback is modeled to provide feedback of position ($N(x,v_4)$) and velocity ($N(\dot{x},v_5)$). Peripheral visual feedback also provides feedback of position ($N(x,v_2)$) and velocity ($N(\dot{x},v_3)$). Proprioceptive feedback is obtained of position, velocity and acceleration, but with constant variance v_1 ($N(q,v_1)$).

The current state estimator computes an estimate of the current state (position, velocity and acceleration) of the hand based on:

(i) The estimate of next state predicted by the internal forward model using knowledge of the previous state, motor command and an internal model of the system dynamics
(ii) Proprioceptive feedback
(iii) Peripheral visual feedback
(iv) Foveal visual feedback

Fig 5.4 shows the weighting functions operating on the different sources of information, as a function of the %distance remaining to target. The weight functions on each source of feedback have been manually selected to provide good performance. As the hand gets closer to the target, the quality of foveal visual information improves, and hence is weighted higher as the hand moves closer to the target. On the other hand, the quality of peripheral information degrades with decreasing distance to target. The reason for this difference between the two modes of visual feedback is that foveal visual feedback is an estimate of the hand's position and foveal information of velocity is just derived from positional information. However, peripheral visual feedback is primary an estimate of the moving hand's velocity – peripheral information of position is just estimated from velocity information. The two modes of feedback differ qualitatively, as foveal information is typically very high resolution information (with less noise and longer propagation delays), whereas peripheral information is typically low resolution information, but with shorter delays.

Proprioception functions the same for feedback of position, velocity and acceleration in terms of weights assigned, noise and delay parameters. Initially, in the beginning of the movement, since vision is required to calibrate proprioception (proprioception is in joint centered coordinates, while vision is in external coordinates), it takes a short time to kick in, but once started, stays constant. Similarly, the quality of information from the forward model stays constant with changing distance to target for the estimation of position, velocity and acceleration. The current state of the hand is estimated using the following sets of equations:

$$x = \frac{w_1}{w_1 + w_3 + w_5 + w_6} x_{fov} + \frac{w_3}{w_1 + w_3 + w_5 + w_6} x_{per} + \frac{w_5}{w_1 + w_3 + w_5 + w_6} x_{prop} + \frac{w_6}{w_1 + w_3 + w_5 + w_6} x_{fwd}$$

$$\dot{x} = \frac{w_2}{w_2 + w_4 + w_5 + w_6} \dot{x}_{fov} + \frac{w_4}{w_2 + w_4 + w_5 + w_6} \dot{x}_{per} + \frac{w_5}{w_2 + w_4 + w_5 + w_6} \dot{x}_{prop} + \frac{w_6}{w_2 + w_4 + w_5 + w_6} \dot{x}_{fwd}$$

$$\ddot{x} = \frac{w_5}{w_5 + w_6} \ddot{x}_{prop} + \frac{w_6}{w_5 + w_6} \ddot{x}_{fwd}$$

where ‘fov’ refers to foveal visual feedback, ‘per’ refers to peripheral visual feedback, ‘prop’ refers to proprioceptive feedback and ‘fwd’ refers to estimation using the internal forward model.

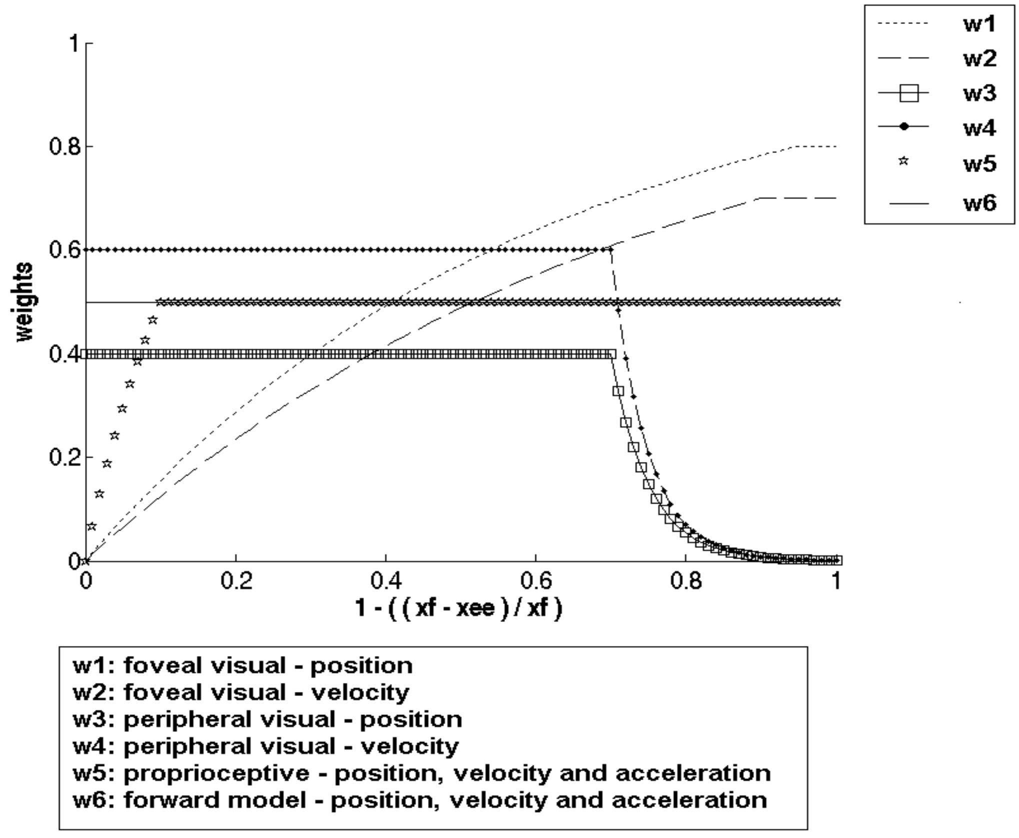


Fig 5.4: Weight functions used by the current-state estimator for 400mm reaches

Left and right single-handed movements

The difference between the performance of the left and the right hand is simulated by changing the maximum acceptable jerk criterion. The left hand is assumed to operate with a much higher weight on the movement's smoothness and lower cost on duration (by modifying 'r') as compared to the right hand, thus indicating that the left hand movement time is typically longer than the right hand's movement time, to comparable target conditions. Typical one-handed simulations of the left and right hand movements to different targets are presented in fig 5.5 and 5.6.

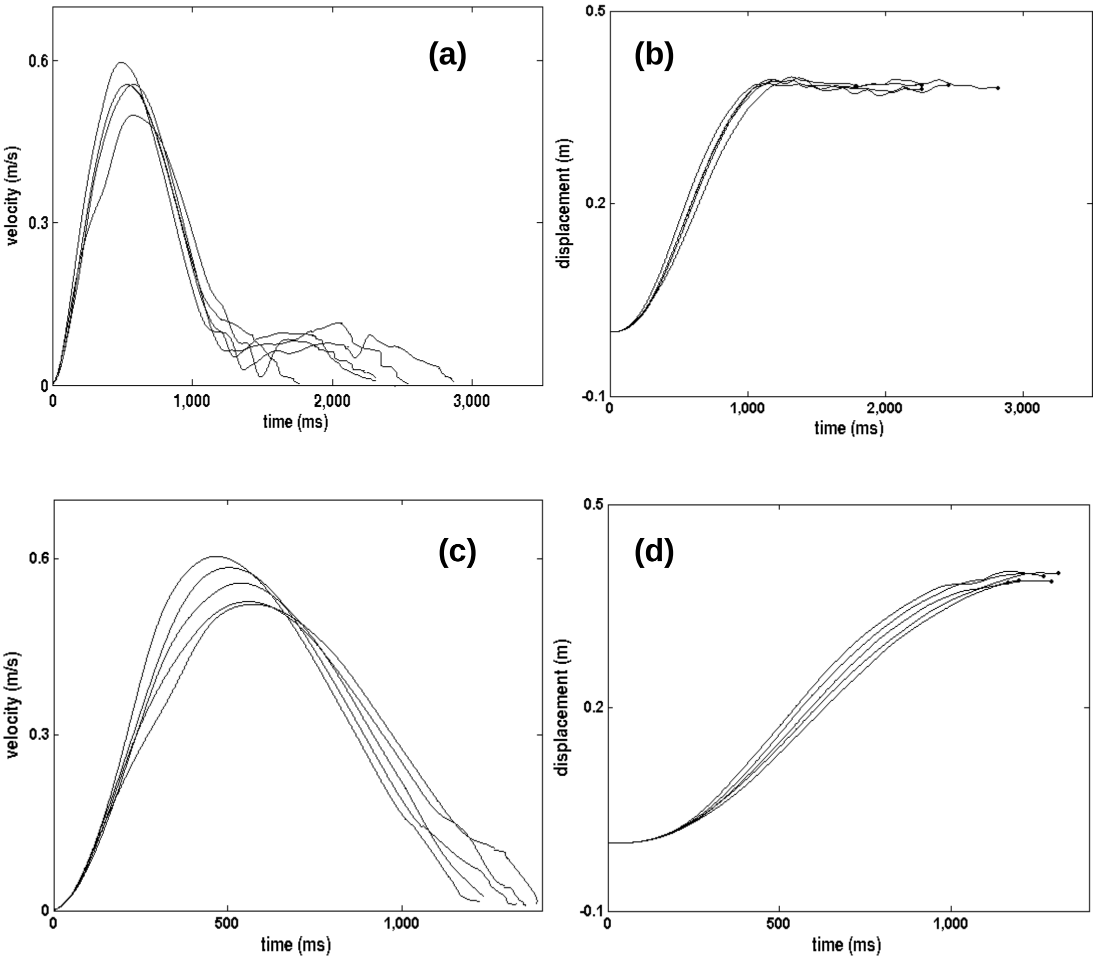


Fig. 5.5: Model simulations of left handed movements; (a), (b) Velocity and displacement profiles when target tolerance is 0mm, (c), (d) Velocity and displacement profiles when target tolerance is 45mm

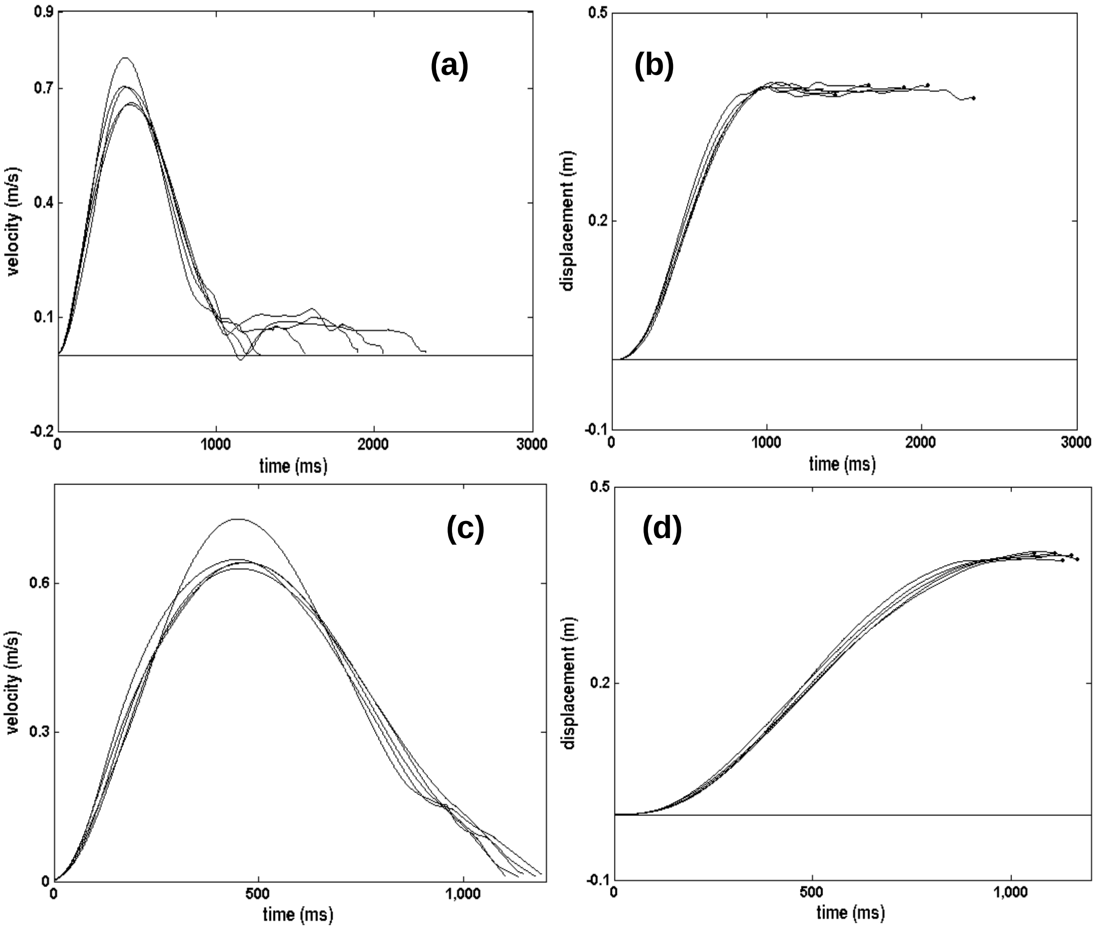


Fig. 5.6: Model simulations of right handed movements; (a), (b) Velocity and displacement profiles when target tolerance is 0mm, (c), (d) Velocity and displacement profiles when target tolerance is 45mm

Two-handed model:

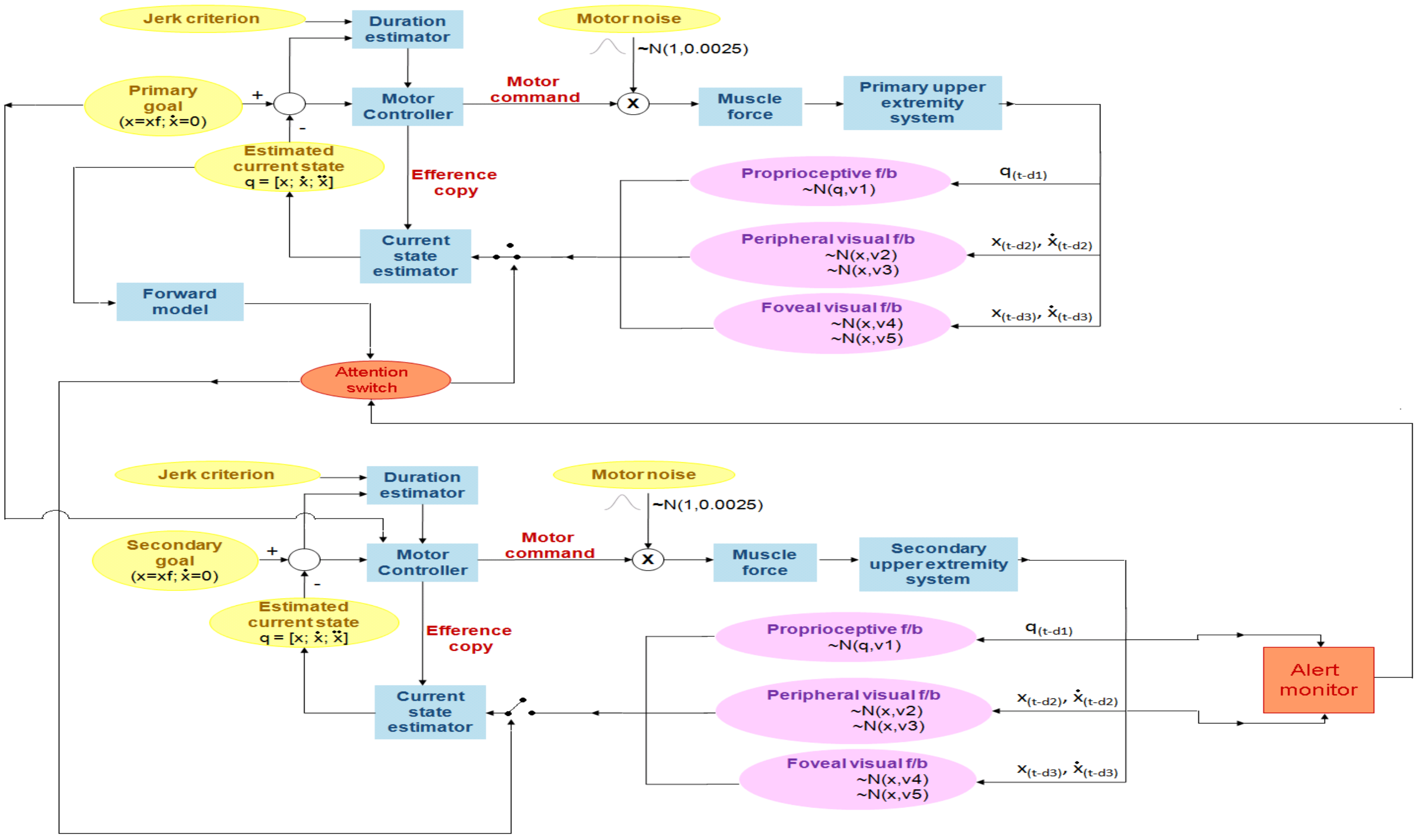


Fig. 5.7: Two-handed control model

The bimanual control model assumes independent controllers for each hand movement. However, while the primary controller receives only the primary task goal as input, the secondary controller receives as inputs both the primary and secondary task goals. The primary hand system works exactly as the one-handed system described in the previous section. The secondary controller generates a motor plan to reach an intermediate target, which is generated as a function of its expectation of when foveal visual feedback would become available (based on primary task goal and secondary task goal). Although this is the conceptual idea, the current model uses empirical values of distance fraction ratios (DFRs) in different circumstances to generate the secondary motor plan. The model assumes that at any point in time, feedback based corrections are processed for only one hand. So while the primary movement is in progress, the secondary hand movement is assumed to proceed based on the initially generated motor plan (open-loop). Although feedback about the secondary hand is 'available' (from prorioceptive and peripheral visual resources), these are not used to process any movement corrections. The alert monitor uses the available feedback information to monitor the movement from a high level. An unanticipated disturbance in the environment would prompt an immediate gaze switch to the secondary target.

As the primary movement proceeds, the forward model uses knowledge of the current state, the updated motor plan and an internal estimate of motor noise to simulate the rest of the movement. If the probability of achieving the task goal with the motor plan (despite the motor noise) exceeds a certain threshold value, then it switches attention to the other task. The secondary task can then process feedback based corrections to achieve the task goal. Differences in the threshold values between subjects and in different trials cause gaze transitions from primary to secondary targets at different points along the trajectory. Thus, both the terminal and predictive strategy behaviors observed in the experiments could be simulated using this model. Although predictive strategies could result in simultaneous placements of both objects at their respective target locations, adoption of the terminal strategy results in sequential completion of the two tasks. Some simulation examples are illustrated in fig 5.8 and 5.9.

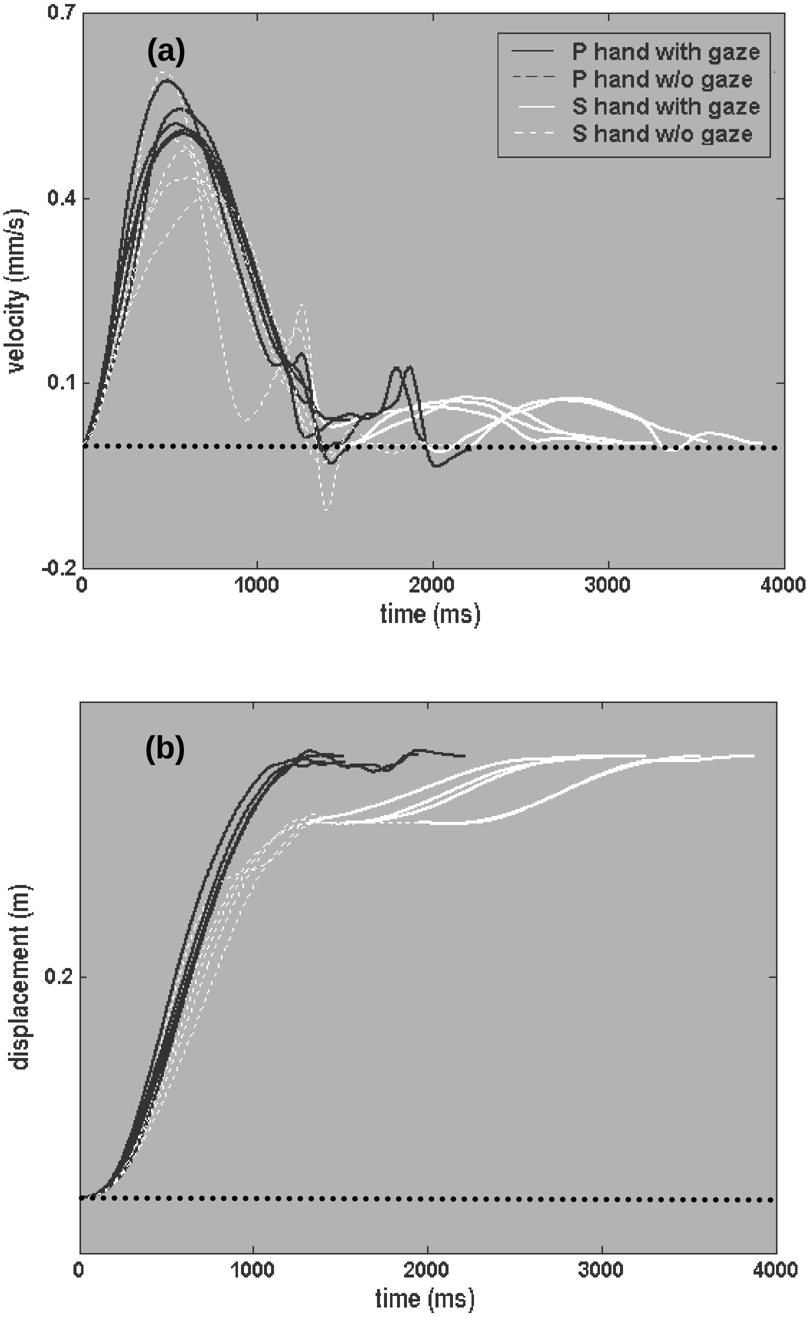


Fig. 5.8: (a), (b) – Velocity and displacement profiles of primary (P) and secondary (S) hand movements to a zero-tolerance target (terminal gaze strategy demonstrated)

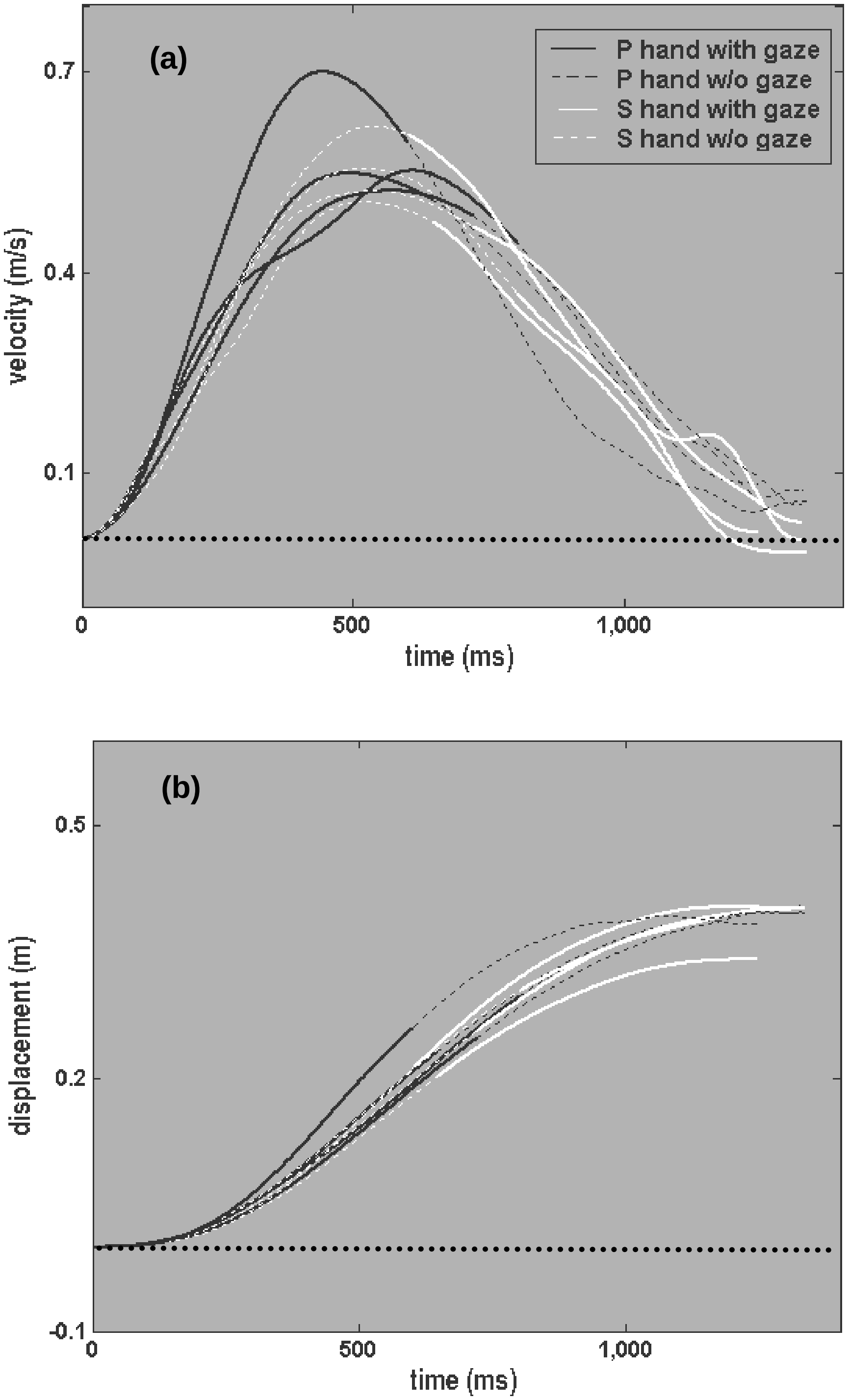


Fig. 5.9: (a), (b) – Velocity and displacement profiles of primary (P) and secondary (S) hand movements to a 45mm tolerance target (predictive gaze strategy demonstrated)

CHAPTER 6

CONCLUSION

Almost 30 years ago, Marteniuk and MacKenzie (1980) suggested that two main themes have emerged (at the behavioral level) in the study of bimanual coordination in humans:

(i) When performing simultaneous symmetrical movements, the control of the two hands appears to be very similar

(ii) When performing simultaneous asymmetrical movements, interference arises between the control of the two hands

Control interferences can be related to the timing or the spatial aspects of movements. In the time domain, when simultaneous movements of different amplitudes have to be produced, the movement times of each hand tend to become similar even though differences exist when the same movements are performed individually (Kelso et al. 1979). Likewise, in the spatial domain, clear assimilation effects have been observed in the spatial characteristics of the two hand movements, like when a circle is drawn with one hand, while simultaneously drawing a line with the other (Franz et al. 1991).

The source of such interference and why the brain finds it easier to produce and control symmetrical, identical movements have been studied extensively. An important objective in this process has been to identify the various task demands and characteristics that modulate the ability to coordinate the hands in space and time. In periodic bimanual coordination tasks, mirror symmetrical movements display both motor and spatial compatibility (Obhi et al. 2005). For example, in a bimanual task involving movements made in the horizontal plane, mirror symmetry means two simultaneous, identical movements made toward the midline. In this situation, the hands move in the same direction with respect to the midline, and the movements are produced by the simultaneous activation of homologous muscles. Thus the fact that symmetrical bimanual movements are easier to perform could reflect a preference for the recruitment of homologous muscles (Riek et al. 1992) or the correspondence between the required movement directions of the two hands (Baldiserra et al. 1982).

It is not entirely clear whether the preference for moving the limbs in the same direction is a result of processing related to motor output or to sensory feedback about the state of the moving limbs. Since many different aspects of coordination contribute to the complexity of a task, processing related to motor output could cause cross-talk at either the programming level or the execution level (Martiniuk and Mackenzie 1980; Martiniuk et al. 1984; Spijkers and Heuer 1995) or both. Motor programming refers to the processes that specify particular parameters of a movement to be initiated, such as amplitude and direction (Heuer et al. 2001). Interference between such programming signals could be due to interactions between different neuronal populations that underlie movements made in particular directions or of different amplitudes (e.g., Laquaniti 1996; Laquaniti et al. 1995). Motor execution has typically been used to refer to motor outflow or efferent signals. Such signals are thought to be absent prior to movement initiation but evolve during the execution process (Spijkers and Heuer 2004). Interference between such execution signals may originate from uncrossed fibers in the pyramidal tract of the descending motor pathways (e.g., Preilowski 1975).

Due to one or more of the above reasons, there is a strong tendency for the two hand movements to be temporally synchronized with each other, unless forced by task-specific constraints or resource limitations to fall out of synchrony. This strong temporal synchrony suggests that a common motor program may be used for both hand movements. However, when presented with two different task demands, the CNS may prioritize one to be the primary task and the other to be the secondary task in order to determine how feedback acquisition and processing resources should be allocated during the course of the movement. The selection of the primary and secondary tasks followed certain specific patterns in the data presented in this study, which suggests that this choice may be a function of the intrinsic abilities of each hand sub-system. But more generally, regardless of the criteria for prioritization, once chosen, the primary task performance may be unaffected by the performance of a concurrent task, and the secondary task may be coupled to the primary task such that it accounts for both concurrent motor performance and sensory feedback limitations.

The key components of a motor program are the movement time, and the relative timing of acceleration and deceleration phases. Hence, although both hand movements might share a common motor plan, depending on the CNS's expectations of the availability of visual feedback, the secondary hand motor program may be "scaled" with respect to the primary hand movement such that it is planned to reach only an intermediate location at the time vision becomes available. This would mean that a specific pattern of movement coupling is 'pre-planned', before movement initiation, in order to ensure that the greatest resource bottleneck, visual feedback, can be shared optimally by the two manual sub-systems. The choice of location of the intermediate target varies as a function of primary hand task difficulty, as this determines when foveal visual feedback of the secondary target would become available to guide the movement of the secondary hand. It also depends on inter-target distance as the separation between the targets determines the quality of visual feedback of the secondary target available until the primary movement is completed and gaze is directed to the secondary target.

From the perspective of the system trying to optimize performance by minimizing movement time, certainly, scaling the secondary program based on expectations of visual feedback seems to be the best strategy. However, our observations indicate that there are some cases in which a predictive strategy is selected over a terminal strategy in target-asymmetric bimanual trials. In the case of using the predictive strategy in such trials, the two hand movements are not synchronized even during the acceleration phases and the resultant movement time of a bimanual movement is much higher than the corresponding trials in which a terminal gaze strategy was used. This suggests that time optimization may not be the only priority, and that there may be either other factors the system is trying to optimize or alternatively that movement generation is not just an optimal process all the time.

Our data have also shown that there are cases in which gaze is moved away from the target being currently aimed at, before movement completion. Such gaze shifts have never been observed in single-handed reach movements, as there is no necessity to look away from the target before movement completion. Fixating a second target even while still moving to the first target suggests that at some point along the movement, the CNS (coordination controller) has decided to continue the primary movement without closed-loop visual feedback of the target or by means of a combination of peripheral visual and proprioceptive feedback (since proprioception has been calibrated using vision in the initial phases of the movement). This feature is modeled by a forward model which internally simulates the entire movement from the current state, using an internal model of motor noise, to estimate if the desired goal would be met. If the probability of achieving the goal exceeds a certain subjective threshold, then the gaze is redirected to the other target demanding attention. This general idea of using an internal model to decide when there is enough information to successfully complete a task without further need for continual closed-loop monitoring is an important step in modeling sequences of actions, where each action execution is contingent on the expectation of a successful performance of the previous actions.

Thus, in terms of pre-planned vs. online control of movements, the specific eye-hand coordination strategy to use in a situation may be pre-planned, and thus the pattern of coupling of the two movements during their acceleration phases is pre-determined. Although the qualitative coordination strategy was planned, motor execution and the sensory consequences of the movements may determine when exactly gaze switches from one target to another and in turn how much longer the secondary movement takes, compared to the primary movement. This hypothesis is supported by the consistent choice of the same eye-hand coordination strategies for a given set of task conditions, but the actual times of movement completion and gaze shifts vary between subjects and successive repetitions of the same trials.

To summarize, some of the important contributions of this work, its applications and some unanswered questions and future work have been listed below.

6.1. Contributions

1. Without specific instructions as to tactics, all subjects evolved with practice, a set of similar eye-hand coordination strategies to use in each particular bimanual task scenario. The different coordination strategies that are used as a function of task precision demand are being reported for the first time.

2. The most optimal way (in terms of movement time) to execute a bimanual task may be to prioritize one task as primary and the other as secondary and not compromise the performance of both tasks. This simplifies the problem of resource allocation without assuming an exclusively symmetric/asymmetric mode of interaction between the two hand systems. A tactic selector is used to model the task prioritization, based on both task difficulties and the inter-target distance. This observation is being reported and modeled for the first time.

3. For these right-handed subjects, the right hand performed better as the secondary hand than did the left hand. Hence, in symmetric bimanual tasks, the left hand was chosen as the primary hand consistently across all subjects and task conditions, indicating an effort to optimize movement time.

4. Temporal symmetry was maintained to the maximum extent possible, while spatial symmetry was compromised in favor of temporal symmetry. This might result from an effort to optimally allocate feedback resources with the minimum number of sub-movements. A reduction in the number of sub-movements would be advantageous both

in terms of motor planning, as well as a biomechanics perspective for movement execution.

5. Although spatial symmetry was compromised, the specific coupling of secondary hand's peak velocity to that of the primary hand varied as a function of task difficulty. The anticipatory scaling of the secondary hand's peak velocity based on the primary task difficulty indicates that movements may be planned with an expectation of when visual feedback would become available.

6. The attention switch component of the model uses an internal forward simulation of the entire movement to estimate if the desired goal would be met and switches attention to the other target if the probability of meeting the goal exceeds a certain subjective threshold. This is a novel way of thinking about multiple task executions – people may use only as much closed-loop feedback control as they "think" the particular task might require before they switch their attention to performing another task.

7. An integrated control model of the left and right hands, together with the gaze system has been developed, to schedule movement components and simulate self-paced bimanual tasks with only high-level inputs. This model sequences the movement phases as a function of task parameters and mediates the optimal allocation of resources (proprioception, peripheral and foveal vision) common to the different subsystems. The model accurately reproduces the diverse spatial and temporal bimanual visuomotor coordination phenomena observed in the laboratory experiment, including task prioritization, gaze transitions and production of realistic multimode hand velocity profiles.

6.2. Applications

1. The Human Motion Simulation Laboratory develops data-grounded

models to predict and evaluate realistic human movements. These models can be used by commercially available human computer aided design (CAD) software to enable ergonomic analysis of products and workplaces. The lab has made considerable efforts to improve the current ability of digital human modeling software to simulate posture and motion for ergonomic analysis.This model of bimanual control is an important step in the development of a general framework that can simulate complex tasks involving multiple movements and object manipulations. This model of bimanual control could potentially be implemented in the HUMOSIM Framework to improve the simulation of hand velocity profiles and gaze transitions in bimanual movements.

2. Methods-Time Measurement (MTM) is a predetermined motion time system that is used primarily in industrial settings to analyze the methods used to perform any manual operation or task and, as a byproduct of that analysis, set the standard time in which a worker should complete that task. MTM is currently limited in its capacity to predict movement times of bimanual tasks, since it classifies such tasks as exclusively symmetric or sequential. This model could be used to predict movement times of bimanual tasks, given the two task difficulty indices and the distance of separation.
3. The 'attention switch' component of the model could be used more generally in single-handed or dual-handed contexts while modeling multiple task executions, where execution of one task is contingent on resources becoming available after the completion of the previous task.
4. The observation that the right hand performs better as the secondary hand as compared to the left hand in bimanual tasks holds important applications for job design. For e.g., if an industrial task requires the execution of sequential sub-tasks, movement time of the overall task can be optimized by designing the job such that the sub-task that needs to be

executed first is required to be performed by the left hand, while the next task is required to be performed by the right hand.

6.3. Future work

Although the dissertation addresses a number of interesting questions on the nature of planning, control and execution of bimanual movements, it has also opened up a series of equally interesting questions yet to be answered and several lines of thoughts worth exploring. Some of these may help prove/disprove the empirical findings, while others might clarify some key assumptions of the model and yet others might help extending both the observations and the model to be applied to a more general class of movements.

1. An important limitation of this study was that the movement distances were constant across all tasks – both unimanual and bimanual. Varying movement distances between tasks, and within tasks (for each hand) and verifying if the observations made in this study are still valid is critical to extending both the findings and the model to think about general bimanual reach movements.

2. All the subjects in this study were right-hand-dominant. Investigating a left-dominant population would be required to verify whether the left-right asymmetry effects are genuinely due to differences in the relative proprioceptive/visual feedback processing capabilities of the two systems or are just incidental due to one hand having been used more extensively in the subject's lifetime and hence operating with better internal models and reduced motor noise.

3. While the visual demand was manipulated using a second target at different distances with respect to the primary target, the proprioception was not manipulated in this study. Either using differential demands on proprioception or working with sections of the population with

proprioceptive disabilities would produce interesting behaviors, which would help us understand and develop the feedback component of the model better.

4. Analyzing data from those sections of the population with impaired left-right hemispherical connections in the motor cortex would also throw more light on the role of each system in mediating coordination.

5. The subjects were instructed to focus only on task accuracy and no emphasis was laid on performance speed. Constraining the task accuracy and/or speed of performance may validate the assumptions about the choice of left/right hand as the primary hand in an effort to optimize movement time.

6. Vision and attention were not differentiated in this study. Introducing a purely cognitive component to some of the tasks, and using different combinations of physical/cognitive workloads on the systems would help establish this difference and would also help to explicitly model the ‘tactic selector’ proposed in this study.

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